TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 773

EXPERIMENTS WITH SUCTION-TYPE WINGS

By O. Schrenk

Luftfahrtforschung
Vol. 12, No. 1, March 28, 1935
Verlag von R. Oldenbourg, München und Berlin

Washington
August 1935

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM NO. 773

EXPERIMENTS WITH SUCTION-TYPE WINGS*

By O. Schrenk

The development of technical flight tends ever more powerfully toward the attainment of highly efficient flight performance, both for normal sport and commercial airplanes as well as for airplanes which serve some sort of special use. In particular the reduction of minimum velocity, i.e., the increase in speed range, has in the last years made progress, the end of which we have as yet by no means reached. Also with regard to climbing ability, absolute ceiling, and maximum speed, demands and performance are in process of growth.

In this development two distinct lines of progress on the aerodynamical side appear: the one concerns itself closely with the hitherto existing, customary forms of construction, and has with the help of additional landing flaps, slotted wings, etc., in steps but steadily and surely led to the improvement of flight performance. It appears, however, that this development will, successful though it has previously been, come to a natural limit within a short time.

Thus the second "revolutionary" type of development is attaining an ever-increasing influence and importance. The fundamentally new types such as the autogiro and helicopter among others, cannot as yet enter into general competition with the usual type of airplanes, yet they bring and promise such progress that further development is undertaken everywhere with the aim of achieving success which is farther reaching than might be hoped from preliminary series of developments.

One must assign an intermediate place in this visible framework to the idea of wing suction. It can be regarded as a fortunate concurrence, that just now, after a long wind-tunnel development, the thought of suction aims at a practical test with airplanes; the development of flight technique itself forces such "byways" to be practically investigated.

---

*"Versuche mit Absaugeflügeln." Luftfahrtforschung, March 28, 1935, pp. 10-27.

The present report collects the investigations of the past years which, while not as yet intended for use in construction, show different possibilities for the building of a suction-type wing and at the same time present some basic explanations concerning the problem of suction.

OUTLINE

Let us call attention once more to the double effect of wing suction. First of all it makes possible the attainment of a substantially higher c_a value, and secondly, allows the profile resistance of an uncommonly thick wing to be so far reduced that it is not much inferior to a normal profile.

In the previous investigation (reference 1) earlier experiments had given for the first time, after many difficulties, profile data for a certain (very thick) suction-type wing which were complete and clear, and therefore could serve as a basis for a further systematic procedure. However, the extent of the results was limited and their trustworthiness could not yet be guaranteed in all points. Lastly, the results of that time could not clarify the conditions of flow sufficiently for further developments.

I. THE CONTENTS AND SUBJECT OF INVESTIGATION*

First of all, the earlier results of the thick profile were confirmed with improved methods of experiment and altered construction of models. They were refined and completed with regard to profile resistance and amount of suction, particularly in the normal c_a region ($c_a <$ 1.5).

The rearmost of the slot locations of that time had proved itself best. Therefore to start with, different widths of the slot in this location were investigated, then two slots of different width located farther to the rear, and finally still two other separate slots.

Subsequently still other special investigations were carried out with these models, such as a measurement of the coefficients; furthermore, a large investigation of the physical nature of suction. To these groups in particular, belong certain boundary-layer measurements as well as experiments with two further slot constructions.

Until then, for wing suction, uncommonly thick wing profiles were used, principally because in them particular experimental and flight technical advantages were seen.

Notwithstanding the manifestly very favorable experimental results, the construction of an experimental suction-type airplane with a thick wing appeared first as somewhat daring, since the airplane would remain hardly able to fly with failure of the suction.

The next task was now this, to show a way in which the flight characteristics could be improved in a similar fashion with suction, while the airplane would be capable of normal flight even with the failure of suction.

Suction experiments on a quite normal profile of usual thickness were postponed and instead a wing was inves-

---

*The work collects, in the form of an extract, four previous reports of the Aerodynamic Experimental Institute for the German aeronautical industry. With regard to many particular details, these reports must be referred to (subsequently designated as Suction Reports I to IV) Ing. B. Winkler, who was particularly active in conducting the experiments.

tigated whose rear end is a landing flap which is deflected downward and where suction takes place in the region of the corner formed there. Two considerations decide the issue of the choice of "suction-type wing with flaps."

1. It was supposed that it would not be possible to attain a c_a value of between 3 and 4 with a normal wing (i.e., thin wing) by means of suction alone without flaps.

2. The high c_a value should be reached with a normal airplane's angle of attack in order to avoid a further difficulty in construction and flight.

The wing with flaps was investigated with two different basic forms of the flaps, with the same area of flap. The aims of these different investigations were on the one hand an aerodynamically clean and consequently favorable flow, and on the other an automatic and unobjectionable lock for the suction slot when the landing flaps are retracted. The present investigation has not succeeded in achieving both of these goals at the same time; either the one or the other could not be completely realized.

After some determinations of coefficients, the behavior of suction-flap wings near the ground was also investigated.

II. THE SCOPE OF THE EXPERIMENTS AND THEIR IMPORTANCE IN FLIGHT TECHNIQUE

The thick profile requires a continuous suction in flight; the thin one with flaps needs suction only in certain circumstances of flight. Consequently the demands put upon the output supply during the experiments were somewhat different in the two cases. In the case of the wing with flaps, it is a question of getting especially favorable values of landing speeds in a short time with full use of the available suction aggregate. This case may be designated "Suction case I".

In the case of thick wings in cruising flight, on the contrary, it is the object, through favorable equalization between propeller output and blower output, to get altogether the most economical use of the available fuel. (Suction case II).

The two suction cases cannot always be simply divided by wing profiles. For example, the thick wing in the landing conditions can be handled in general as Suction case I.

What the significant performance factors are in the two cases is shown in the following sections where various factors are represented in detail, which in the previous publication (reference 1) were given only shortly or incompletely:

a) Resultant pressure force and lift.- The lift was not determined by weighing, but for a particular cross section of the profile was found from pressure-distribution measurements. From these the "resultant pressure force" R, was obtained, which one may imagine split up into the components of lift A and drag W_d. Since the ratio W_d/A is small in practice, we can approximate (in magnitude, but not according to direction)

$$R = A \quad \text{and} \quad c_r = c_a{}^*$$

b) Angle of attack.- α is the experimentally measured angle; α_∞ is the corresponding angle of attack for infinite span and infinite jet. On account of the quite unusual ratio between model size and channel size, the difference between α and α_∞ is very large. As it could not be determined by theoretical considerations, α_∞ was determined from the direction of R which is given by the pressure distribution. α_∞ is exactly perpendicular to A; for R this does not quite hold exactly, but still approximately. A small correction, dependent on the value of W_d was estimated and added where it seemed necessary.

c) The quantity of air removed by suction.- The quantity of air removed by suction $Q\left(\frac{m^3}{s}\right)$ is given by the dimensionless coefficient

$$c_Q = \frac{Q}{vF}$$

*It may be mentioned that for very high c_a values (3 and more) with usual aspect ratios also, the c_a value receives a correction and indeed a decrease of substantial size, which is connected with the normal induced resistance. If momentarily we designate by c_{a_∞} the value for infinite aspect ratio, then $c_a = c_{a_\infty} \cos a_i$ where a_i is as usual the induced angle of downwash. For normal wings $\cos a_i \approx 1$.

where v is the velocity, F the surface of the wing, and $c_Q t$ (t=chord) may be designated as "thickness of flow" of the air disappearing inside the wing.

d) The suction pressure.- This is given by

$$c_p = \frac{p}{\frac{\rho}{2} v^2}$$

This definition indicates a reversal of the sign compared to that previously given, according to which p was the suction under pressure. c_p will generally be negative. (The previous definition had in certain cases given inconsistencies in meaning.)

e) The coefficients of suction independent of velocity.- The data concerning quantity and pressure of the suction blower become more appropriate as far as the airplane is concerned if we do not make them dimensionless with respect to wind resp. flight velocities, but instead use the quantities characteristic of the airplane, namely, airplane weight G and wing surface F. We obtain then

$$\frac{c_Q}{c_a^{1/2}} = \frac{Q}{\sqrt{\frac{2}{\rho} GF}}$$

and

$$\frac{c_p}{c_a} = \frac{p}{G/F}$$

These two factors have a direct relation to the quantity of air removed by suction and to the suction pressure of a particular airplane in stationary straight flight and by multiplication with the fixed constants for the airplane $\sqrt{\frac{2}{\rho} GF}$ and $\frac{G}{F}$, we obtain the values Q and p themselves.

f) The pure suction work (not given in the results) is equal to $-Q\,p$*, the dimensionless coefficient is equal to $-c_Q\,c_p$*.

*$-Qp$ respectively $-c_p\,c_Q$ positive, because p resp. c_p is negative.

g) The total blower work depends in addition on the flow resistances in the air ducts and on the cross section of the surface opening. If we neglect the flow resistances, which are to be as small as possible, then the total blower work is equal to

$$-Qp + Q \frac{\rho}{2} v_b^2$$

and in terms of the dimensionless coefficient

$$-c_Q \ c_p + c_Q \frac{v_b^2}{v^2}$$

The air velocity in the exit section of the blower v_b is connected with the size of exit cross section F_b by the relation $Q = v_b F_b$. F_b itself will, under certain circumstances, be given by constructional viewpoints.

h) The sink resistance.- One part of the resistance of the profile W_Q, the sink resistance, can be given immediately. Its value is

$$W_Q = \rho \ Q \ v$$

It is caused by the indrawn air which gives up its entire forward momentum to the wing according to the impulse theorem. Its dimensionless coefficient is

$$c_{w_Q} = \frac{W_Q}{\frac{\rho}{2} v^2 F} = 2c_Q$$

How and where this impulse transfer takes place, whether by pressure or friction, is unimportant as far as the magnitude of W_Q is concerned, and is probably also different from case to case.

i) The measured and total profile resistance.- The total profile resistance of the wings, which is designated for the moment as W_∞', consists of W_Q and a remainder W_∞. By means of weighing, W_∞' could be measured, but on the other hand, by the use of the impulse method first given by Betz (reference 2), it is possible to obtain the remainder W_∞ exactly, as can be seen from a consideration

in connection with the original work by Betz. For the total profile resistance, we obtain

$$W_\infty' = \rho\, Q\, v + W_\infty$$

or, in dimensionless coefficients

$$c_{w_\infty}' = 2c_Q + c_{w_\infty}$$

c_{w_∞}, as the result of the impulse method, is contained in the table of results.*

k) The reaction effect.- The quantity of air removed by suction in case II will be blown, if possible, to the rear. For all states of flight except for landing, we are interested in the resulting reaction shock which tends to unload the propeller. The resulting forward thrust is

$$\Delta W = -\rho\, Q\, v_b$$

or, in dimensionless coefficients

$$\Delta c_w = -2\, c_Q\, \frac{v_b}{v}$$

Cases in which the air is not ejected toward the rear, require special consideration.

l) The resistance coefficient to be overcome by the thrust of the propeller.- This is with the reaction shock:

$$c_{w_\infty} + 2c_Q \left(1 - \frac{v_b}{v}\right)$$

As can be seen from the above, it may become equal to zero or even negative, depending on the magnitude of v_b. For $v_b = v$ it is exactly equal to c_{w_∞}. This relation holds only for air ejected toward the rear.

*About the tabulated evaluation of the impulse measurements, see Suction Report I.

A certain unevenness in the lift distribution may, as mentioned above, increase the weighed resistance to some extent without any noticeable effect in c_{w_∞}.

m) The decisive performance factors in Suction case III (see ch. II a.A.).- When it is a question of principally decreasing the landing velocity, the cross section F_b of the blower exit is made as large as possible, and the corresponding blower output obtained according to paragraph g). For the start, on the other hand, our aim is to make F_b a little smaller for use of v_b in reaction effect. A general discussion of the performance relations for start and climb is possible in general form; however, it is generally carried through more easily for the individual case as structural requirements generally change the consideration to some extent.

n) The "equivalent profile drag".- the decisive performance factor in Suction case III.- This is composed of the blower work and the propeller work. The "equivalent profile drag" coefficient is obtained as the sum of the individual values g) and l).* For given values c_Q, c_p, and c_{w_∞} it is also dependent on v_b; that is, F_b. Calculations show that for $v_b = v$, it has a minimum value of

$$c_{l'_\infty} = c_w + c_Q (1 - c_p)$$

Concerning c_{l_∞}, measurements show the following:** Increasing c_Q requires for a constant c_a a decrease of c_{w_∞} and an increase of $c_Q (1 - c_p)$. For a certain particular c_Q (and consequently also c_p, c_{w_∞}) the sum of the two, c_{l_∞}, assumes a minimum value for all measurements at the same c_a.

This minimum value of c_{l_∞} is obtained by two entirely different minimum conditions (optimum value concerning quantity of air suction and optimum value concerning exit cross section of blower), and gives the minimum equivalent profile drag with which the particular c_a can be obtained.

*This is based on the approximate assumption of equal efficiency of propeller and blower; with small changes these considerations may also be carried over for unequal efficiencies, but for a rapid survey the assumption of equal efficiencies seems justified because of its simplicity.

**Compare also figure 5 above, and section IV; also remark to figure 5.

The set of these points for different c_a values forms together the "equivalent profile drag polar" (see fig. 5 above) of the suction-type wing, which in Suction case II may be made the basis of aerodynamic airplane design.

If, in the case of an airplane, the correct dimension of F_b for obtaining the minimum value c_{l_∞} is not possible, or at least not for all flight conditions, then we obtain for $v_b = v$, the equivalent profile drag coefficient $= c_{l_\infty} + c_Q \left(1 - \frac{v_b}{v}\right)^2$.

III. ARRANGEMENT AND METHODS OF EXPERIMENT

The essential details of the experimental arrangement are shown in figure 1. They are: end plates on the side of the wing (in order to obtain a uniform 2-dimensional lift distribution), rigid suspension of the model (no measurement of the forces by weighing), measurement of air quantities by means of nozzles, measurement of profile resistance by means of the pitot-tube rake according to the impulse method as given by Betz, measurement of lift by means of drilled holes arranged around the profile at the middle of the wing for obtaining the pressure distribution.

For obtaining the series of pressure-distribution measurements, suction pressure and profile resistance measurements, two photographical multiple manometers had been built.

The investigation of each measured point was made in the following fashion: First, the suction was started, then the wind was started up. The behavior of the flow was observed and checked simultaneously with the measurements (manometer exposure, measurement of stagnation pressure, and nozzle pressure for determination of quantity of air removed by the blower system). The evaluation (reading, plotting, determination of areas) was made at the conclusion of a series of experiments.

A series of checks, corrections, and special considerations which were required to make sure of the results before the principal investigation, cannot be individually mentioned here. (Compare, for instance, Suction Report I, section 5.)

The measurements for the most part were carried out in a small 1.2-meter (3.94-foot) wind tunnel of the Aerodynamical Laboratory, and at wind velocities between 23 and 30 m/s (75.44 and 98.40 ft./sec.), and so at coefficients between 7,000 and 9,000, i.e., Reynolds Numbers of between 5×10^5 and 6.3×10^5.

IV. EXPERIMENTS AND RESULTS WITH A THICK WING PROFILE

Figure 2 shows the thick profile with the location of the drilled holes for pressure measurement; figure 3 gives the eight different slot configurations. The slots I-IV correspond to positions aft of slot III of the previous investigation; slot I was also, as far as the width was concerned, behind slot III. Slot VIII possesses a rounded rear edge but is otherwise the same width as slot III.

The tables I to VIII contain excerpts of the results obtained with these slots. The complete tables, as well as also all figures, are contained in Suction Report I. Omitted are the values of c_{l_∞}, $\frac{c_Q}{c_a^{1/2}}$, $\frac{c_p}{c_a}$ which can be calculated from the previous data as well as such repetitions as have shown agreement.

To illustrate one case completely by figures, the results of slot IV are repeated in figures 4 and 5. Figure 4 above shows as the envelope of the individual series of measurements the curve for the required minimum quantities of air at a particular c_a.

Figure 4 below (some other slots showed this even more distinctly) shows that with a certain scatter, the resistance is dependent essentially only on c_Q.

Also the graphs of c_p vs. c_Q for the thick profile show again a pretty uniform "path." Especially distinctly is this shown with slots I to IV and VIII (forward position of slot), less distinctly it is also present for rearward position of slots V and VI.*

*The pressure distribution curves of figures 12 and 13 indicate the reason for this behavior. The suction slot is located approximately where all of the pressure-distribution curves cross. Thus there exists approximately con-
(Continued on next page)

In figure 5 above we see how, according to the explanation of Section II n), we find a minimum value of c_{l_∞} for each space α and how the "equivalent profile drag polar" becomes the envelope.

In figures 6 to 11, which give the comparison of the individual arrangements, all small differences are intentionally neglected in order to emphasize more clearly the essential influences. Slots III and VIII coincide completely in the results except for the resistance.

The conclusions which we can draw from the comparison of the different results are the following:

a) The slot width at a particular slot position has no influence on the required quantity or on the type of flow. This holds at least as long as the slot width remains within a certain limit, which in the case of slot VII has already been passed; also slot VI seems for smaller quantities of flow to be already somewhat too wide. The suction under pressure and so also the suction and "equivalent profile drag" are, on the other hand, as is to be expected, dependent on the width of the slot.

b) The detail construction of the slot edges, whether round or sharp edges, does not seem to have decisive significance. The rounding of the rear slot edge is not at all noticeable; rounding of the other edge is, according to previous discussions, equivalent to a certain widening of the slot. (See reference 1.)

c) The position of the slot is of very considerable influence on the results:

1. For the rearward position of the slots V and VI the required quantities of air are roughly 40 percent larger than for the forward position. The cause is the longer path of flow up to the slot. (See also V.)

2. The required suction under pressures are less for the rearward position of the slot because the suction pressures on the profile are less there. (Compare also figs. 12 and 13.)

(Continued from p. 11)
stant pressure independent of c_a. Consequently when removing the same quantity of air by suction, the difference in pressure between the outside of the slot and the suction chamber is roughly the same and thus the inside pressures will also coincide.

3. The profile output polar for the same width of slot is generally more favorable for the forward position of the slot.

4. The shape of flow in the region between slot and rear edge is somewhat different in the two cases. This can be seen from the magnitude of the α_∞ required for a certain c_a; also on observations with streamers, and finally on the course of the pressure-distribution curves (figs. 12 and 13). These show clearly that the forward position of the slot is somewhat too far forward from the aerodynamical point of view because behind it the pressure rise stops already ahead of the rear edge. This flattening of the pressure curve is well known as an indication of the vicinity of the separation flow. This is also the reason why, with the forward position of the slot at the same angle of attack, smaller lifts are reached.

d) One of the most significant factors, and one which all slots have in common, is the strong decrease of c_{w_∞} compared to that of the same profile without suction. As its c_{w_∞} is approximately equal to 0.05, we succeed by means of suction to effect a decrease to 1/3 or 1/4 of its starting value even for small values of c_a. Even if we compare c_{l_∞} instead of c_{w_∞} then for small c_a and c_Q the decrease remains still under 1/3.

The considerable scatter of the c_{w_∞} values is doubtless due, in addition to certain faults of the series method of measurement, to the fact that the resistance is not determined as usual as the mean value over the entire span, but is taken as the value at a particular profile cross section where local differences cannot compensate themselves. From some results and check calculations, we find in addition that the hardly avoidable small reduction of the smoothness of model surface in the course of the experiments with changes of the model, has a certain effect on the results. This indicates that with suction wings, great emphasis is to be put on clean construction and care of the wing surface.

Special experiments carried out in the large 2.2-meter (7.22-foot) wind tunnel were concerned with the required quantities of air for "pulling back" flow which has already separated. This experiment was not possible in a small tunnel because the jet was deflected very much

by the large model. For values of $c_a \approx 2$ these experiments gave air quantities of approximately 125 percent, for values of $c_a \approx 3$ a quantity of air of 130 percent of the minimum quantity.

Also carried through in the 2.2-meter tunnel was a series of experiments for determination of coefficients with slot I. In the course of this experiment the required minimum pressures and quantities were determined for fixed angle of attack corresponding approximately to $c_a = 2.3$. Both of these decreased continuously by a small amount between Reynolds Numbers of 2.5×10^5 to 9×10^5. To a smaller extent the corresponding c_a values followed the same course. Altogether conditions with increasing Reynolds Number up to 10^6 seem to become somewhat more favorable, or at any rate not worse.

V. BOUNDARY LAYER REMOVAL BY SUCTION AND SINK ACTION*

Certain experiences in the course of research work have again called attention to the physical phenomena which lie at the basis of the suction effect. Their explanation seemed necessary to a further development. Especially the fact that, contrary to previous expectations, slots which lie so near the rear edge as V and VI are still effective, did not seem explainable according to the old conception of boundary-layer removal by suction.

The old theory of suction was simply this: The strongly retarded parts of the boundary layer in a region of pressure rise are removed by suction before they cause separation of the total flow; thereupon a new boundary layer is formed which can again overcome a certain pressure rise.

Now the question arose as to whether the "sink influence," i.e., the change in the statical pressure on the surface due to the suction, is not essentially connected with the formation of the newly achieved form of flow.**

*Compare also O. Schrenk, Z.f.a.M.M., vol. 13, 1933, p. 180.
**This problem was first investigated further in a contribution by Professor Prandtl (not yet published) on a total representation of aerodynamics; also, and independent therefrom, in Suction Report I, of the author. Similar questions, however, without the correct consideration of the boundary layer, have also been raised by others.

The sink influence consists of a flattening out of the pressure rise before and after the slot, which, in the immediate vicinity of the slot, is even converted into a pressure drop. (See fig. 14, where the actual flow with sink influence has been denoted by circles, the calculated main flow without sinks by crosses.) It arises by the superposition of the suction flow which is directed radially toward the slot and the main flow which runs approximately parallel to the surface. According to Bernoulli, the pressure difference between the two is at each point approximately

$\frac{1}{2}\rho(v_a + w)^2 = \frac{1}{2}\rho v_a^2 + \rho v_a w + \frac{1}{2}\rho w^2$

$$\Delta p = \pm \rho \ v_a \ w$$

$\frac{1}{2}\rho v_a^2$

$\rho v_a w + \frac{1}{2}\rho w^2$

where v_a is the free main flow (independent of sink influence) and w is the velocity of the sink flow (small, compared to the main flow).

It is clear that this change of the pressure field must prepare a more favorable path for the development of the boundary layer which does not lead so rapidly to separation. The required quantity of air for suction is then (contrary to the old conception), in no particular ratio to the quantity of the boundary layer. The quantity required for suction must, however, be made so large that the two pressure rises (practically the one ahead of the slot is decisive) are just yet bearable (German "ertragbar") for the development of the boundary layer. An essential difference between the two suction theories is this: that the real boundary-layer suction acts only toward the rear, i.e., downstream, while the sink influence is effective both in the front and in the rear.

Actually the two phenomena will generally appear coupled; the conceptions are, however, also justified insofar as we can give independent examples of each. For the pure boundary-layer removal, we can imagine a body whose surface consists of a fine-meshed sieve or of a porous mass. For the sink influence we can consider the wing with suction at the rear edge. The problem of the investigation of this section was, therefore, only a practical one, namely, to show which effect predominates in the measured and similar sections, and which of the two concepts is therefore more suitable for a working theory.

The previous investigations had shown: slots considerably farther forward than slot I are unsuitable because then the flow separates ahead of the rear edge of the

wing; on the other hand, it was recognized that slots farther aft than V could furnish an aerodynamically good flow with a certain increase of the quantity of air removed by suction. Why the most effective slots lie aft of the half chord can also be explained by considerations which are not immediately concerned with the nature of the suction.* However, the complete state of affairs is not fully cleared up by such a manner of consideration.

A consistent explanation is obtained, however, if we add the "sink effect toward the front." Some further investigations have shown that the sink action is actually intimately connected with the suction process.

If the theory of sink influence is correct then, as mentioned before, a suction from the rear edge of the wing must be possible. Slot X (fig. 15) corresponds practically sufficiently closely to this boundary case. As was to be expected, by means of a sufficiently large quantity of air removed by suction, the flow could be kept clinging to the wing. The required quantity is roughly three times as large as for slot I and roughly, twice as large as for slot V. From a practical standpoint, this result has little importance.

The actual proof for the large contribution due to the sink effect has been given by another experiment. (See fig. 16.)

For a slot as illustrated in figure 16, it can be proven that no sink effect can arise in the pressure field if the width of the slots is equal to the thickness of the layer of air to be removed. If, therefore, the presence of a sink effect is absolutely necessary for the suction effect, a quantity corresponding to the width s will not be useful, and only such contributions beyond this value will act favorably. The quantity of air has to increase with increasing width of the slot.

This increase in the minimum amount of air was most strikingly proved by experiment. In this case the slot was located at about the same position as the previous

---

*Where greater velocities occur, correspondingly large pressure rises are also overcome.

slots V and VI. The results obtained are:

α	s, mm	c_Q	c_p
30°	4	0.022	-8.5
30°	5.5	.023	-7.3
30°	8.5	.041	-3.2
30°	12.5	.054	-2.6

The smallest value of c_Q for s = 4 mm (0.157 in.) corresponds approximately to the value of the plane slot, all others being larger.

The result will be even more intuitive if we consider the corresponding curves of the pressure distribution (fig. 17). Disregarding a parallel displacement, which will be discussed in the following paragraphs, the curves agree very well in the forward region of increase in pressure; also in the region of the sink effect near the slot where, without an overlapping rear edge, we ought to obtain considerably different pressures for different quantities of air. Apparently the creation of a just sufficient sink effect was decisive for the magnitude of the quantity of air.

In connection with the above-mentioned parallel displacement, the magnitude of the real boundary-layer removal may be recognized. This parallel displacement is caused by the fact that for the two smaller amounts of air no considerable increase in pressure has to be overcome behind the suction slot; i.e., in this case the amount of air is too small for the actual boundary-layer removal, whereas for the two larger quantities of air both boundary-layer removal and sink effect are acting.

Still earlier there was an idea to make practical use of such designs as slot IX, since in this case the air would flow in with less suction pressure, by itself, so to speak. However, the results show that this is not of practical value after the sink effect becomes of importance.

An investigation of the boundary layer itself also gave the same results concerning the sink effect.

A method of calculation as developed by Gruschwitz (reference 3), was applied to calculate from the boundary-layer measurements on the suction wing for slot locations

I and V, if and where separation would occur in front of the slot without sink effect (fig. 14). Disregarding for the present all details, the result obtained is that for slot V; without the sink effect the flow would have separated far ahead of the slot, whereas with the sink effect it will, for the minimum quantity of air, just be able to stay on. Obviously in this case the sink effect is decisive. The result is not so definite for slot I. The calculations show that without the sink effect the flow would separate approximately in the region of the slot. It does not seem possible as yet to draw definite conclusions from this.

VI. EXPERIMENTS WITH FLAP PROFILES*

The section with the four different designs of flaps investigated is shown in figure 18. Flap I is so designed that the slot does not open until the flap moves. This first design has the advantage of a smooth and at the same time a safe slot lock.

For flap II (a and b) it was considered advisable to neglect an automatic slot lock in order to clear up the removal of some aerodynamic disadvantages of design I. For design II the slot is located behind the curved part of the leading edge of the flap. For flap IIc the suction slot is moved into the rearmost portion of the curved part, thereby guaranteeing automatic locking of the slot for zero deflection of the flap.

Figure 19 shows the meaning of angles α and β and the distance a. The moment (c_{m_h}), which in some cases has been determined from the pressure distributions similarly as the center of pressure, has been given for the leading edge as reference point (fig. 18), while the moment of the flap has been given for the hinge of the flap as reference point. The pressures inside the chamber have been measured at station p. (See fig. 18.)

Tables IX to XXI give the most important results of these arrangements, again in summarized form.

The values of c_p and c_Q have been measured rather

---

*The investigation of the flap profiles has been suggested by Mr. H. B. Helmbold.

high and unfavorably due to the comparatively narrow cross sections inside the wing.*

Unfortunately it was impossible to avoid limiting the number of samples of the curves in this case, since the angle β appears as another parameter. A complete representation may be found in Suction Report III.

For flap IIa, the results have been represented completely in figures 20 to 24, 26, and 29. A representation of c_{l_∞} is not necessary in this case. (Suction case II in sec. II will hardly occur here.)

The results show that concerning the quantity required for a certain c_a region, a definite flap deflection is always most favorable in all cases:

$\beta =$	15°	up to	c_a	$= 2$
	30°	" "	c_a	$= 2.8$
	45°	" "	c_a	$= 3.3$
	60°	for	c_a	beyond these values

c_a values obtained without suction $(c_Q = 0)$ up to about 2 are important in case of emergency (failure of suction).

The fluctuation of the flow for $\beta = 60^\circ$ below $\alpha = 10^\circ$ has happened since then in several other cases. Hereby the flow fluctuates irregularly about 2 to 5 times per second between the separated and the unseparated case. These irregularities may have their origin in two aerodynamic sources of instability: first, a curved surface with pressure increase (suction curvature), and second, an edge which "deviates" the flow (such as organ pipes), both acting under unfavorable circumstances.

---

*Inside of the wing the pressure decrease from the closed to the open part of the wing follows approximately an exponential law. The local distribution of the magnitude of the suction will be of the same character. As an exact analysis shows, this tends to increase the values of the experimental results; however, it is not possible to estimate the resulting errors more accurately.

The values c_p and c_{w_∞} for the wing with flaps, depend not only on c_Q but also very much on the angle of attack; i.e., the lift, contrary to thick and rigid sections. Furthermore, they vary with β, such that an increase in β causes larger values of c_p and c_{w_∞}. All curves, however, seem to show that the conditions of the flow are rather complicated.

Comparing all three (four) flap devices, we obtain the following results (see also figs. 25 to 33 and the tables):

a) With the exception of the suction pressures, flaps IIa and IIb do not differ very much. Concerning the quantity of air, IIb seems slightly more favorable. For IIb the flow does not fluctuate for $\beta = 60^\circ$.

b) Concerning the quantity of air required for a definite value of the lift, IIc seems almost always most favorable. I is better than IIa for lifts up to 3.3; for the rest they are equal. The region of c_a for favorable consumption of quantities of air for values of β differs very much for different flaps.

c) For corresponding suction pressures the order seems to be a little different. For very high c_a values which are decisive for the strength of the blower, IIc is not as good as the other two which, for a rough consideration, are nearly equal. For smaller values of β and c_a the conditions are just about the same. Unfavorable for IIc, in addition to that, is the fact that the suction pressures increase very fast due to the narrow slot if the quantity of air is larger than the minimum quantity.

d) For IIa the profile drag is usually very small ($\approx$0.005 to 0.02). It is larger for IIc ($\approx$0.01 to 0.04) and it is largest for I ($\approx$0.01 to 0.07). In the case of landing, larger profile drag is not undesirable if no other disadvantages are connected with it. However, for these high values of c_a these differences will be negligible compared to the induced drag.

e) Considerable differences occur for the angles of attack. For flap IIa high values of c_a, above 3.5, may be obtained for values of α between 3° and 14°. For flap I, α has to be above 14°; IIc lies in between and

needs angles of attack of 10° and more. For the actual airplane there is an additional induced angle of attack. Therefore small angles α may be desirable concerning the landing gear.

From the theoretical curves in figure 26, we may see how the actual flow approximates the frictionless pure potential flow. For flap IIa the differences compared to the theory are about the same as for ordinary wings with boundary-layer removal; however, they are considerably larger for I and IIc.*

f) Moments about the Y axis are somewhat smaller for I and IIc compared to IIa.

For $c_a = 3.5$: IIa, $c_m = 1.3$ to 1.45;

I and IIc, $c_m = 1.2$ to 1.35.

For the smooth section it might be mentioned that the c.p. is almost fixed.

g) The efficiency of the flap can be represented by $\frac{d\ c_a}{d\ \beta}$. For IIa this value is about 0.06 (in degrees);

" IIc " " " " 0.033;

" I " " " " 0.03 and less.

For ordinary ailerons of the same chord, $\frac{d\ c_a}{d\ \beta}$ is about 0.05.** From the present designs it may be concluded that certain differences occur for the flow for different designs of flaps. By means of some streamlines, figure 18 shows the conditions as observed by means of strings.

In cases IIa and IIb, the flow follows the contour of the section smoothly until the trailing edge; for case I

---

*The calculation upon which these curves are based is an extension of Glauert's method (reference 4). Glauert's method was extended for larger values of β and α and also for finite thickness of wing sections by approximations based upon the well-known theory of Joukowsky sections.

**Calculations based upon experiments of Petersohn and Higgins and Jacobs (reference 5).

the separation begins almost always at the rear edge of the slot; case IIc lies in between. It is obvious that different values of c_{w_∞} must result from this. Differences in the values of α_∞, c_{m_h}, and $\frac{dc_a}{d\beta}$ are caused by the fact that the flap with the wake acts like a flap with a smaller β.

To understand these differences in the flow, it is necessary to study the pressure and flow conditions at such a sharp deflection by building up the (actual) flow from its components. According to the laws of the potential flow, the pure deflection is connected with an underpressure which increases in the first part of the deflection and decreases in the second. Therefore, we obtain pressures which vary a great deal from point to point. If, as in the case of the wing with flaps, the edge is located in a field of increasing pressure, then this pressure will be flattened out in front of the edge by the above-mentioned decrease in pressure. In most cases it will even become reversed, while it will be increased by the increase in pressure. Slot I is located so that its forward sink effect cannot be made useful, since it lies in a region of decreasing pressure, anyhow (as explained above). Furthermore, the slot is located in a region of very fast-changing pressure and therefore acts similarly to the rather wide slot VII in figure 3. Part of the high increase in pressure which has its origin aft of the deflection, lies behind the slot and at once starts another separation. For slot IIa, however, the most effective forward sink effect is moved into the second part of the deflection; i.e., in the region of the most dangerous increase in pressure. However, aft of the slot the flow follows the contour smoothly until the trailing edge of the wing. The experiment with slot IIc shows that it is not possible to change the location of slots IIa and IIb very much in order to obtain an automatic slot lock, since even now a very small displacement changes the flow very much. Figure 34 shows one of the pressure distributions characteristic for flap wings with boundary layer removed.

In a few cases the coefficient $c_{fl} = \frac{M_{fl}}{q\,b\,t^2_{fl}}$ (coefficient of the flap moment M_{fl}) was determined similarly to c_a and c_{m_h}. Since the calculation is based upon very few experimental points, the result obtained is not very accurate and therefore can only give the order of magni-

tude of the values varying with α, c_a, and c_Q, the following values have been found for flap IIa:

For $\beta = 15^\circ$	c_{f1} =	0.14 to 0.18
30°		.28 " .33
45°		.35 " .56
60°		.42 " .59

For separated flow the above listed values are decreased by 20 to 50 percent. For the following series of Reynolds Numbers, which unfortunately are very limited for experimental reasons and for $\beta = 45^\circ$ and $\alpha = 20^\circ$ (IIa), we obtain the following values:

R.N.	c_r	c_Q	c_p
2×10^5	3.20	0.019	-3.1
4×10^5	3.15	.017	-2.9
5×10^5	3.10	.016	-2.7

A decrease of the minimum quantities of air and minimum pressures required is connected with a decrease in the resulting lift. On the average, the result does not become worse.

Experiments with flap IIa concerning the effect of the distance from the ground disclosed that for equal quantities of air removed, the lift becomes smaller for decreasing distances from the ground (tables 22 to 25). An interpolation of the measured points shows the maximum possible lift decreasing from:

$$c_r = 3.75 \text{ to } 3.45 \quad \text{for } \frac{a}{t} = 2 \quad \text{for } c_Q = 0.03$$

$$c_r = 3.75 \text{ " } 3.70 \quad \text{" } \frac{a}{t} = 1 \qquad \beta = 45^\circ$$

(For the measuring of a, see fig. 19.) For equal c_r the suction pressures remain nearly constant.

Regarding the ground effect, a high-wing design seems to be preferable when this type of wing is used, and very

close to the ground, it will be necessary to have a maximum amount of suction for a short time, or the gliding motion will be superimposed by a downward acceleration which is some part of the acceleration of the earth.

An aerodynamic explanation for this decrease in lift which occurs even though the effect of pressure on the pressure side increases near the ground, is given as follows: For the flap deflected, the direction of the flow will be changed very much toward the ground; at the ground it will at once be directed toward the rear. In the angular space between flap and ground, we obtain a damming effect which causes increasing pressures on the suction side of the flap, and lower velocities at the flap compared to those without ground effect. Disregarding the region closest to the trailing edge, we can make the rather rough assumption that the flow along the wing section with the ground effect will be similar to that without the ground, thus obtaining a relation between lift and quantity of air. The decrease in the required quantity of air to be removed is proportional to velocities; the lift of the suction side, however, decreases faster (Bernoulli's law). The result is that near the ground we obtain a smaller value for c_a for the same c_Q.

VII. OUTLOOK FOR FLIGHT TECHNIQUE

Without going into details of construction, we can estimate from the experimental results the performances to be obtained in flight; i.e., estimate the improvement due to removal of the boundary layer.

It will be possible to:

Increase the speed range;
Increase the rate of climb and the ceiling;
Reduce take-off and landing distance.

Other improvements such as higher loadings at take-off are closely connected with the above-mentioned ones.

It might be mentioned that very thick wing sections may, under certain circumstances be very valuable for both useful space and structures (strength).

The consideration, results of which will be presented

here, hasbeen made in the following way: A clean airplane with flaps, however, without suction (boundary-layer removal), has been compared with two suction airplanes - one of them with a thick wing section, the other with the thinner flap section. All three airplanes are supposed to have equal cruising speed, equal weight, and equal rest resistance (F_{wr}) for equal engines. We therefore will obtain differences regarding the wing area and small differences also in the weight.

The following notation has been used:

M_I = airplane without suction (wing area = F_I)

M_{II} = airplane with suction with thick wing section (wing area = F_{II})

M_{III} = airplane with suction with flap section (wing area = F_{III})

The following tabulation gives all the numerical values upon which the calculation has been based - (Numerical values for M_{II} and M_{III} corresponding to the experimental results):

	$c_{w_{p_{min}}}$	$c_{a_{max}}$	$\frac{c_{a_{max}}}{c_{w_{p_{min}}}}$	$\frac{F_{wr}}{F}$
M_I	0.0095[a)]	2.4[d)]	253	0.018[f)]
M_{II}	.0150[b)]	4.0[e)]	267	g)
M_{III}	.0115[c)]	3.6[e)]	313	g)

a) Estimated from results of good wing sections.
b) c_{l_∞} instead of c_{w_p} (suction case II, ch. II).
c) Without suction; $\beta = 0$; thicker section than for M_I.
d) With lift flap.
e) $c_{a_{max}}$ depends on the allowable suction.
f) Value approximately corresponding to good airplanes.
g) Has to be transformed on account pf the wing areas F_{II} and F_{III} to be determined:

$$\frac{F_{wr}}{F_{II}} = 0.018 \frac{F_I}{F_{II}}, \text{ etc.}$$

For the consideration of the maximum altitude (ceiling) the following values have been selected:

For M_{II} the results with slot IV (c_{l_∞} in fig. 4)

For M_{III} the few measured points of flap IIa (for $\beta = 15^\circ$ and 30°)

For M_I values have been estimated, since convenient experimental values were not at hand. These values may be a little conservative:

$$c_a = 1 \qquad c_{w_p} = 0.018$$

$$c_a = 1.2 \qquad c_{w_p} = .025$$

$$c_a = 1.5 \qquad c_{w_p} = .035$$

$$c_a = 1.8 \qquad c_{w_p} = .045$$

The aspect ratio of M_I has been selected so that $\frac{F}{b^2} = 0.04$ (aspect ratio 8:1). The thickness of the wing sections at the root: M_I: 20 percent; M_{II}: 45 percent; M_{III}: 20 percent.

As mentioned before, the wing section of airplane M_I decreases faster toward the wing tip than that of M_{III}.

All three airplanes are supposed to have equal cruising speed for equal engine performance and equal rest resistance. Neglecting the induced drag, we therefore obtain different wing areas:

$$F_{II} = F_I \frac{0.0095}{0.0150} = F_I\ 0.63$$

$$F_{III} = F_I \frac{0.0095}{0.0115} = F_I\ 0.83$$

For equal weights the minimum velocity is proportional to $\sqrt{\frac{c_{w_{p_{min}}}}{c_{a_{max}}}}$*. Thus we obtain:

---

* Since $q_{min} = \frac{c_{w_{p_{min}}}}{c_{a_{max}}} \frac{G}{\frac{\eta N}{\frac{\rho}{2} v^3} - F_{wr}}$.

$$v_{min_{II}} = 0.975\ v_{min_I}\ (0.96\ v_{min_I})$$

$$v_{min_{III}} = 0.9\ v_{min_I}\ (0.91\ v_{min_I})$$

For constant chord the wing spar of M_{II} becomes a little higher and thus a little lighter; the wing spar of M_{III} a little lower and therefore a little heavier than that of M_I. The rest of the weight proportions of the airplane also change slightly. Estimating all these influences, we obtain the values as given in the above parentheses.

It may be seen that there is an advantage in the speed range compared to highly developed airplanes without suction which, however, is not as yet very remarkable, and we have to aim for further increase in $c_{a_{max}}$ or decrease in c_{w_p} or c_{l_∞}.

Introducing a law for the dependence of the engine performance on the altitude in the region of maximum ceiling, we will be able to estimate the differences in the maximum ceilings of M_I, M_{II}, and M_{III} without making other assumptions about wing and power loading.*

Concerning M_{II} we can even make another step. For equal span the chord length of M_{II} decreases to 0.63 compared to M_I. In spite of this decreased chord, the height of the spar at the wing root is greater than that of M_I, namely, $0.63 \times 0.45\ t_I = 0.285\ t_I$ against $0.2\ t_I$ for M_I. Instead of making the spar a little lighter, as in the case of M_{II}, we can increase the span without increasing the spar section, thus increasing the allowable load. Its $\frac{I}{c}$ (moment of resistance) is $\frac{0.285}{0.2} = 1.43$ times greater than that of F_I for equal cross section; the span can be increased by $\sqrt{1.43} = 1.196$, while chord length and depth of spar may be decreased by $\frac{1}{1.196}$ until full utilization of the $\frac{I}{c}$ of the spar for the same cross section has been obtained. Unfortunately, the new spar will be a little heavier.

---

*However, not for the ceilings themselves. For the method of calculation, see reference 6.

The airplane thus obtained may be called M_{II}^x since it has the same wing area as M_{II}. Regarding climbing performance, it will be better than M_{II} and M_{III}.

The following values for the differences in maximum ceiling have been obtained:

M_{II} against M_I: $\Delta H \approx 0.55$ km (0.75 km)

M_{III} " M_I: $\Delta H \approx .4$ " (0.3 ")

M_{II}^x " M_I: $\Delta H \approx 1.6$ " (1.6 ")

Also the speed at maximum altitude has been calculated:*

$$\frac{v_{g_{II}}}{v_{g_I}} \approx 1.1$$

$$\frac{v_{g_{III}}}{v_{g_I}} \approx 0.95$$

$$\frac{v^x_{g_{II}}}{v_{g_I}} \approx 1.2$$

It may be mentioned that for several reasons the values of ΔH and v_g cannot be accurate values.

To obtain rate of climb and time to climb, we have to make assumptions about wing loading and power loading, also about the performance of the engine in all altitudes between sea level and maximum ceiling. The results depend too much on the choice of special conditions, so that it does not seem very useful to give numerical values. Numerical investigations, however, prove again the superiority of the "suction" airplane, especially M_{II}^x.

Defining the landing run as the path of the airplane from a certain altitude (depending on the landing field) to the final stop, we see that two values are important for its magnitude: the landing speed of the airplane and the gliding angle when approaching the ground.

---

*Effects of weight have been estimated and accounted for.

The landing speed was given previously. The landing run will in some way also be slightly affected by differences in weight (for the airplanes investigated).

Concerning the gliding angle, the slower airplanes, M_{II} and M_{III} are slightly superior to M_I since $\frac{W_i}{G} = \frac{G}{\pi q b^2}$. For M_{II}^x, however, this advantage vanishes on account of larger span. Altogether, M_{II} and M_{III} will be better than M_I; M_{II}^x, however, nearly equal or slightly less favorable in landing run.

Similar to rate of climb and time to climb, the take-off distance depends on the engine and propeller performance and especially, on the wing and power loading, and cannot be easily determined. At any rate, one knows that the take-off distance is primarily determined by the pressure head q_a (at the instant the airplane leaves the ground) and the maximum angle of attack φ of the airplane. (Take-off distance = the distance from the beginning of the rolling until a prescribed altitude has been reached.) The pressure head may approximately correspond to that of the maximum angle of attack. Based upon the experimental results for the ceiling, the angle of attack can be assumed to be larger for the "suction" type airplane, especially for M_{II}^x than for M_I (without suction). The aerodynamic pressure q_a of the best angle of attack is smaller for M_{II}^x (very likely also for M_{II} and M_{III}) than for M_I, so that a remarkable decrease in the take-off distance may be expected for the "suction" type airplane, especially for M_{II}^x.

For completeness we might mention that the basis for comparison changes very greatly as soon as the service conditions are altered. Thus, for instance, we might in some cases neglect a high velocity at low altitudes or, on the other hand, just aim for such a high velocity. Such conditions have to be investigated separately. Without doubt, a further development of the suction wing will be possible and necessary.

Thus the thick wing section will very likely be superior to any other design as soon as it is possible to obtain c_{l_∞} values of 0.01 instead of 0.015 at cruising flight. Further experiments in this direction are planned.

As to the wing with flaps, the following problems are important:

Design of a flap with an automatic locking device for the slot at zero position of the flap which, however, has the same advantage as IIa with regard to a small angle of attack required (see sec. V);

Decrease in the quantity of air to be removed and in the suction work;

Application of suction to thin sections with smaller values of c_{w_p} for $\beta = 0$.

It is a question as to whether or not fundamentally different forms will be developed in the future. At the present time the thicker wing sections seem to have more possibilities for future development. However, it will not be applicable for small airplanes since failure of suction might bring the airplane into a dangerous situation. Sufficient safety could be obtained by distributing the entire "suction" upon several aggregates.

Thus a thick wing section will very likely not represent the first step for the application of boundary-layer removal. It will be advisable to use smaller airplanes with flaps which will be able to fly without "suction," in order to investigate all the major difficulties of suction airplanes.

VIII. CONCLUSIONS

Two suction wings have been investigated: a thick-wing section with a thickness ratio of 40 percent with slots of various widths and at various stations (figs. 2 and 3) and a flap wing with various designs of flaps and suction slots (fig. 18). With flap at zero position, the flap wing had almost no c.p. travel. Its thickness ratio was 20 percent.

In varying the slots of the thick section, it was important to find the most efficient location of the slot:

1. To obtain maximum values for $c_a(c_r)$ for minimum suction.

The landing speed was given previously. The landing run will in some way also be slightly affected by differences in weight (for the airplanes investigated).

Concerning the gliding angle, the slower airplanes, M_{II} and M_{III} are slightly superior to M_I since $\frac{W_i}{G} = \frac{G}{\pi q b^2}$. For $M_{II}{}^x$, however, this advantage vanishes on account of larger span. Altogether, M_{II} and M_{III} will be better than M_I; $M_{II}{}^x$, however, nearly equal or slightly less favorable in landing run.

Similar to rate of climb and time to climb, the take-off distance depends on the engine and propeller performance and especially, on the wing and power loading, and cannot be easily determined. At any rate, one knows that the take-off distance is primarily determined by the pressure head q_a (at the instant the airplane leaves the ground) and the maximum angle of attack φ of the airplane. (Take-off distance = the distance from the beginning of the rolling until a prescribed altitude has been reached.) The pressure head may approximately correspond to that of the maximum angle of attack. Based upon the experimental results for the ceiling, the angle of attack can be assumed to be larger for the "suction" type airplane, especially for $M_{II}{}^x$ than for M_I (without suction). The aerodynamic pressure q_a of the best angle of attack is smaller for $M_{II}{}^x$ (very likely also for M_{II} and M_{III}) than for M_I, so that a remarkable decrease in the take-off distance may be expected for the "suction" type airplane, especially for $M_{II}{}^x$.

For completeness we might mention that the basis for comparison changes very greatly as soon as the service conditions are altered. Thus, for instance, we might in some cases neglect a high velocity at low altitudes or, on the other hand, just aim for such a high velocity. Such conditions have to be investigated separately. Without doubt, a further development of the suction wing will be possible and necessary.

Thus the thick wing section will very likely be superior to any other design as soon as it is possible to obtain c_{l_∞} values of 0.01 instead of 0.015 at cruising flight. Further experiments in this direction are planned.

As to the wing with flaps, the following problems are important:

Design of a flap with an automatic locking device for the slot at zero position of the flap which, however, has the same advantage as IIa with regard to a small angle of attack required (see sec. V);

Decrease in the quantity of air to be removed and in the suction work;

Application of suction to thin sections with smaller values of c_{w_p} for $\beta = 0$.

It is a question as to whether or not fundamentally different forms will be developed in the future. At the present time the thicker wing sections seem to have more possibilities for future development. However, it will not be applicable for small airplanes since failure of suction might bring the airplane into a dangerous situation. Sufficient safety could be obtained by distributing the entire "suction" upon several aggregates.

Thus a thick wing section will very likely not represent the first step for the application of boundary-layer removal. It will be advisable to use smaller airplanes with flaps which will be able to fly without "suction," in order to investigate all the major difficulties of suction airplanes.

VIII. CONCLUSIONS

Two suction wings have been investigated: a thick-wing section with a thickness ratio of 40 percent with slots of various widths and at various stations (figs. 2 and 3) and a flap wing with various designs of flaps and suction slots (fig. 18). With flap at zero position, the flap wing had almost no c.p. travel. Its thickness ratio was 20 percent.

In varying the slots of the thick section, it was important to find the most efficient location of the slot:

1. To obtain maximum values for $c_a (c_r)$ for minimum suction.

2. To obtain small values for "equivalent drag" for values of c_a for long-range flight. (Equivalent drag = thrust work to overcome the profile drag + suction work; equivalent drag coefficient c_{l_∞} defined as c_a and c_w.)

As to the different designs of flaps, it was important to obtain a suction slot which opens automatically with the flap deflection and is free from certain aerodynamic disadvantages of design I (separated flow over the flap, large values of α to obtain large values of c_a). It has not as yet been possible to design such a flap.

The results of the thick wing section are: With regard to c_{l_∞} for small values of c_a, slot IV is better than VI and as good as I to III and V ($c_{l_\infty} = 0.015$); with regard to the suction work at large values of c_a, it is much better than all others.

Concerning the angle of attack required, slots V and VI are better; c_a values have been measured up to 3.5. However, the limit of c_a depends only on the magnitude of the suction work and according to previous experiments could be raised up to 5.

With regard to $c_{a_{max}}$ the results of the flap wing are similar - no measurements being obtained for $c_a = 3.8$. For $\beta = 45^\circ$ and 60° (for β, see fig. 18), c_a values of 3.6 to 3.8 have been obtained compared to $c_a = 2$ at equal β for the wing without suction. Slot I is a solution for the attempted automatic locking device. Slots IIa and IIb give a good flow on the flap (minimum α required). IIc represents an intermediate solution, the conditions of flow being between I and IIa. (See fig. 18.)

Near the ground the $c_{a_{max}}$ values for the flap wing decrease very fast. (For explanation, see end of section VI.)

Some statements have been made about the physical reasons which determine the unusual types of flow and the large c_a values obtained (sec. V). Besides the actual boundary-layer removal (i.e., removal of the dangerous layer close to the wall, which causes separation), there is

a large contribution by the sink effect: The additional flow directed toward the slot, i.e., the "sink flow" changes the entire pressure field along the surface forward and aft of the slot so that separation occurs less rapidly (fig. 14). Both phenomena contribute to the actual conditions and are therefore necessary for a clear conception.

General considerations show some, though not very great advantages of the two wings investigated over highly developed profiles without suction but with flaps.* The following factors were discussed: speed range, flight at maximum ceiling, landing and take-off distance.

Future possibilities are briefly indicated.

Translation by Wm. Bollay and H. M. Antz,
Guggenheim Aeronautics Laboratory,
California Institute of Technology.

---

*Here $c_{w_p} = 0.0095$ and $c_a = 2.4$.

REFERENCES

1. Schrenk, O.: Experiments with a Wing from Which the Boundary Layer is Removed By Suction. T.M. No. 634, N.A.C.A., 1931.

2. Betz, A.: A Method for the Direct Determination of Wing-Section Drag. T.M. No. 337, N.A.C.A., 1925.

3. Gruschwitz, E.: The Process of Separation in the Turbulent Friction Layer. T.M. 699, N.A.C.A., 1933.

4. Glauert, H.: A Theory of Thin Aerofoils. R. & M. No. 910, British A.R.C., 1924.

5. Petersohn, E.: Theoretische und experimentelle Untersuchung der unter Einwirkung von Querrudern an Tragflügeln auftretenden Momente. Luftfahrtforschung, vol. II, no. 2, 1928, p. 44.

   Higgins, George J., and Jacobs, Eastman N.: The Effect of a Flap and Ailerons on the N.A.C.A. M6 Airfoil Section. T.R. No. 260, N.A.C.A., 1927.

6. Everling, E., and Fuchs, R.: Die Berechnung von Steigzeiten für verschiedene Luftdichten, Höhen und Belastungen. Technische Berichte, vol I, 1917, p. 42.

   Schrenk, M.: Calculation of Airplane Performances without the Aid of Polar Diagrams. T.M. No. 456, N.A.C.A., 1928.

Table I. Thick wing. Slot I.

α	c_r	$c_{w\infty}$	c_Q	$-c_p$
—10°	0,84	0,0083	0,0088	2,50
—10°	0,77	0,0092	0,0074	2,14
—10°	0,72	0,0098	0,0058	1,74
—10°	0,68	0,0107	0,00401	1,39
—10°	0,60	0,0115	0,00264	1,07
—10°	0,55	0,0128	0,00170	0,95
—10°	0,50	0,0135	0,00126	0,81
—10°	0,46	0,0139	0,00083	0,77
—10°	0,43	0,0150	0,00055	0,65
—0,1°	1,33	0,0096	0,00607	1,83
—0,1°	1,34	0,0107	0,00495	1,59
—0,1°	1,31	0,0095	0,00423	1,43
—0,1°	1,30	0,0099	0,00341	1,25
—0,1°	1,25	0,0112	0,00303	1,16
+9,8°	2,27	0,0050	0,0178	5,46
+9,8°	2,13	0,0060	0,0130	3,66
+9,8°	2,06	0,0076	0,0092	2,50
+9,8°	2,01	0,0092	0,0073	2,00
+9,8°	1,97	0,0102	0,0065	1,81
+9,8°	1,95	0,0111	0,0056	1,64
20°	2,70	0,0111	0,0099	2,58
20°	2,63	0,0101	0,0094	2,31
30°	3,41	0,0085	0,0154	4,3
30°	3,43	0,0079	0,0171	4,9
30°	3,52	0,0047	0,0213	6,9

Table II. Thick wing. Slot II.

α	c_r	$c_{w\infty}$	c_Q	$-c_p$
—10°	0,66	0,0101	0,00369	1,18
—10°	0,60	0,0102	0,00282	1,05
—10°	0,58	0,0110	0,00229	0,99
—10°	0,56	0,0117	0,00181	0,91
—10°	0,55	0,0119	0,00147	0,85
—10°	0,52	0,0124	0,00114	0,80
—10°	0,49	0,0141	0,00097	0,77
—10°	0,48	0,0145	0,00084	0,74
—10°	0,47	0,0150	0,00063	0,69
—10°*)	0,51	0,0130	0,00170	0,87
—10°	0,49	0,0154	0,00119	0,81
—10°	0,45	0,0157	0,00084	0,73
—10°	0,44	0,0180	0,00062	0,67
—10°	0,43	0,0194	0,00039	0,61
0°	1,33	0,0090	0,00421	1,27
0°	1,28	0,0100	0,00313	1,08
0°	1,25	0,0113	0,00254	0,97
+9,8°	2,17	0,0062	0,0117	2,41
+9,8°	2,12	0,0072	0,0090	1,95
+9,8°	2,04	0,0076	0,0076	1,70
+9,8°	2,02	0,0087	0,0068	1,56
+10°	2,00	0,0082	0,0066	1,50
+20°	2,69	0,0095	0,0100	1,94
+30°	3,34	0,0095	0,0149	2,77

Table III. Thick wing. Slot III.

α	c_r	$c_{w\infty}$	c_Q	$-c_p$
—10,1°	0,64	0,0108	0,00385	1,13
—10,1°	0,61	0,0114	0,00275	1,00
—10,1°	0,55	0,0124	0,00192	0,90
—10,1°	0,51	0,0131	0,00130	0,80
—10,1°	0,49	0,0137	0,00086	0,75
—9,9°*)	0,54	0,0140	0,00131	0,83
—9,9°*)	0,48	0,0169	0,00053	0,68
—0,1°	1,45	0,0084	0,00698	1,52
—0,1°	1,36	0,0099	0,00423	1,19
—0,1°	1,40	0,0088	0,00579	1,39
—0,1°	1,31	0,0105	0,00312	1,02

*) Recheck

Table III. Continued

α	c_r	$c_{w\infty}$	c_Q	$-c_p$
0°*)	1,32	0,0131	0,00355	1,13
0°*)	1,30	0,0120	0,00357	1,12
0°*)	1,26	0,0137	0,00281	1,01
0°*)	1,25	0,0146	0,00268	0,98
+9,8°	2,26	0,0043	0,0186	3,07
+9,8°	2,18	0,0053	0,0132	2,26
+9,8°	2,09	0,0071	0,0093	1,74
+9,8°	2,00	0,0075	0,0065	1,39
+9,8°	1,99	0,0095	0,0065	1,41
+9,8°	1,95	0,0101	0,0057	1,30
+9,8°	1,88	0,0111	0,0053	1,25
+20°	2,63	0,0100	0,0093	1,62
+30,3°	3,33	0,0066	0,0147	2,31

Table IV. Thick wing. Slot IV.

α	c_r	$c_{w\infty}$	c_Q	$-c_p$
—10°	0,64	0,0100	0,00395	1,08
—10°	0,59	0,0103	0,00263	0,95
—10°	0,52	0,0119	0,00167	0,83
—10°	0,47	0,0147	0,00106	0,72
—10°	0,42	0,0176	0,00066	0,65
—10°	0,40	0,0194	0,00040	0,60
+0,1°	1,38	0,0097	0,00482	1,21
+0,1°	1,34	0,0098	0,00389	1,10
+0,1°	1,29	0,0111	0,00326	1,03
+0,1°	1,28	0,0119	0 00290	0,98
+0,1°	1,26	0,0127	0 00256	0,92
+9,9°	2,13	0,0091	0,0107	1,75
+9,9°	2,09	0,0079	0,0087	1,56
+9,9°	2,03	0,0093	0,0073	1,42
+9,9°	2,00	0,0101	0,0060	1,27
+9,9°	1,98	0,0095	0,0056	1,21
+20°	2,68	0,0084	0,0099	1,54
+30°	3,29	0,0084	0,0144	1,91

Table V. Thick wing. Slot V.

α	c_r	$c_{w\infty}$	c_Q	$-c_p$
—10°	0,84	0,0088	0,00775	1,15
—10°	0,77	0,0097	0,00538	0,93
—10°	0,72	0,0107	0,00377	0,77
—10°	0,62	0,0108	0,00237	0,59
—10°	0,56	0,0124	0,00162	0,50
—0,15°	1,64	0,0067	0,0093	1,28
—0,15°	1,58	0,0075	0,0069	1,01
—0,15°	1,51	0,0081	0,0056	0,89
+9,7°	2,36	0,0031	0,0205	2,46
+9,7°	2,28	0,0032	0,0181	2,02
+9,7°	2,26	0,0033	0,0161	1,78
+9,7°	2,20	0,0048	0,0126	1,41
+9,7°	2,15	0,0055	0,0101	1,25
+19,9°	3,05	0,0022	0,0233	2,66
+19,9°	2,99	0,0026	0,0195	2,21
+19,9°	2,93	0,0036	0,0172	1,91
+19,9°	2,89	0,0038	0,0158	1,75
+30°	3,67	0,0035	0,0350	4,13
+30°	3,69	0,0032	0,0320	3,69
+30°	3,62	0,0022	0,0284	3,16
+30°	3,64	0,0020	0,0267	2,94
+30°	3,57	0,0023	0,0257	2,82
+30°	3,57	0,0022	0,0247	2,08

Table VI. Thick wing. Slot VI.

α	c_r	$c_{w\infty}$	c_Q	$-c_p$
—10°	0,69	0,0114	0,00386	0,77
—10°	0,60	0,0139	0,00241	0,60
—10°	0,51	0,0151	0,00168	0,51
—10°	0,51	0,0148	0,00152	0,49
—0,2°	1,44	0,0089	0,00712	1,00
—0,2°	1,37	0,0098	0,00562	0,86
+10°	2,17	0,0072	0,0113	1,25
+10°	2,12	0,0075	0,0102	1,15
+19,9°	2,86	0,0060	0,0157	1,46
+19,9°	2,86	0,0061	0,0150	1,40
+30°	3,57	0,0026	0,0224	1,85

Table VII. Thick wing. Slot VII.

α	c_r	$c_{w\infty}$	c_Q	$-c_p$
—10°	0,57	0,0162	0,00540	0,82
—10°	0,53	0,0174	0,00380	0,74
—10°	0,47	0,0209	0,00236	0,64
—10°	0,42	0,0240	0,00167	0,56
+20°	2,90	0,0081	0,0221	1,55
+29,8°	3,67	0,0032	0,0594	2,37

Table VIII. Thick wing. Slot VIII.

α	c_r	$c_{w\infty}$	c_Q	$-c_p$
—10°	0,68	0,0116	0,00393	1,17
—10°	0,59	0,0126	0,00258	0,98
—10°	0,53	0,0135	0,00168	0,86
—10°	0,49	0,0150	0,00105	0,76
—0,1°	1,37	0,0097	0,00488	1,32
—0,1°	1,32	0,0104	0,00388	1,16
—0,1°	1,29	0,0119	0,00314	1,07
—0,1°	1,24	0,0146	0,00253	0,95
—0,1°	1,18	0,0164	0,00224	0,90
+9,8°	2,02	0,0088	0,0074	1,58
+9,8°	1,97	0,0112	0,0060	1,37
+9,8°	1,93	0,0124	0,0054	1,25
+9,8°	1,89	0,0157	0,0046	1,14
+19,9°	2,61	0,0112	0,0090	1,57
+29,9°	3,25	0,0090	0,0131	2,06

Table IX. Wing, with flap I. $\beta = 15°$

α	c_r	$c_{w\infty}$	c_Q	$-c_p$	c_{mh}
12°	1,20	0,0300	0	—	
24°	2,46	0,00736	0,01712	5,27	0,72
24°	2,36	0,01455	0,01240	3,04	
24°	2,23	0,0227	0,00918	1,89	
24°	1,46	0,0512	0	—	
30°	2,78	0,0113	0,0190	5,32	
30°	2,65	0,0165	0,01603	3,88	
32,3°	2,92	0,0158	0,02103	5,5	

Table X. Wing, with flap I. $\beta = 30°$

α	c_r	$c_{w\infty}$	c_Q	$-c_p$	c_{mh}
0°	1,04	0,0270	0,00320	1,64	
0°	0,97	0,0333	0,00217	1,36	
0°	0,97	0,0413	0,00145	1,15	
0°	0,96	0,0465	0,00094	1,04	
0°	0,93	0,0504	0,00068	0,95	
0°	0,83	0,0574	0	—	
12°	1,85	0,0269	0,00719	2,17	
12°	1,74	0,0283	0,00471	1,59	
12°	1,73	0,0365	0,00320	1,27	
12°	1,68	0,0409	0,00229	1,08	0,68
12°	1,68	0,0570	0,00124	0,90	
12°	1,52	0,0792	0	—	
18°	2,227	0,0325	0,00963	2,48	
18°	2,163	0,0327	0,00674	1,76	
18°	2,103	0,0381	0,00434	1,23	
18°	2,078	0,0467	0,00301	0,96	
18°	1,85	0,0794	0	—	
24°	2,83	0,0162	0,01775	4,01	
24°	2,62	0,0279	0,01257	2,56	0,93
24°	2,49	0,0335	0,0089	1,54	
24°	1,58	0,154	0	—	
30°	3,35	0,0154	0,0232	4,63	
30°	2,96	0,0267	0,0166	2,63	1,03
34,5°	3,47	0,0187	0,0258	4,28	

Table XI. Wing, with flap I. $\beta = 45°$

α	c_r	$c_{w\infty}$	c_Q	$-c_p$	c_{mh}
0°	1,47	0,0542	0,00765	2,98	
0°	1,36	0,0477	0,00538	2,56	
0°	1,33	0,0513	0,00373	2,31	
0°	1,26	0,0598	0,00240	1,89	
0°	1,05	0,1262	0	—	
12°	2,13	0,0464	0,0097	2,94	
12°	2,08	0,0476	0,0068	2,41	0,76
12°	2,06	0,0543	0,00477	2,16	
12°	2,04	0,0604	0,00411	2,07	
12°	1,72	0,1158	0	—	
18°	2,58	0,0415	0,0136	3,52	
18°	2,52	0,0492	0,0091	2,64	
18°	2,45	0,0547	0,0057	2,02	
19°	2,06	0,1276	0	—	
24°	3,09	0,0260	0,0217	4,83	
24°	3,05	0,0290	0,0195	4,31	1,01
24°	2,93	0,0307	0,0176	3,83	
24°	2,90	0,0321	0,0150	3,27	
24°	2,86	0,0405	0,0130	2,83	
24°	2,80	0,0466	0,01056	2,30	
24°	2,76	0,0580	0,00848	1,72	0,915
24°	2,70	0,0613	0,00804	1,62	
24°	1,40	—	0	—	
30°	3,36	0,0210	0,0246	4,63	
30°	3,31	0,0281	0,0219	3,95	
30°	3,15	0,0471	0,0166	2,35	
33°	3,58	0,0206	0,0277	4,68	1,23
33°	3,38	0,0335	0,0226	3,05	1,18
34,8°	3,79	—	0,0319	5,15	
34,8°	0,98	—	0,0309	2,23	

Table XII. Wing, with flap I. $\beta = 55.6^\circ$

α	c_r	$c_{w\infty}$	c_Q	$-c_p$	c_{m_h}
0°	1,6	0,0624	0,00827	3,47	
0°	1,6	0,0634	0,00585	3,35	
0°	1,58	0,0631	0,00400	3,09	
0°	1,42	0,1395	0,00285	1,67	
0°	1,20	0,1708	0	—	
12°	2,32	0,0503	0,0097	3,47	
12°	2,28	0,0530	0,0067	3,12	
12°	2,25	0,0847	0,0048	2,70	0,86
12°	1,91	0,1473	0,0032	0,86	
12°	1,83	0,1612	0	—	
18°	2,76	0,0452	0,0141	3,96	
18°	2,72	0,0462	0,0094	3,22	
18°	2,61	0,0669	0,0057	2,55	
18°	2,40	0,0998	0,0053	1,24	
18°	2,17	0,1426	0	—	
24°	3,18	0,0366	0,0221	4,93	
24°	3,06	0,0400	0,0154	3,68	
24°	2,98	0,0511	0,0113	2,74	1,03
24°	2,82	0,0763	0,0090	1,81	
24°	1,39	—	0,0106	0,86	
30°	3,59	0,0310	0,0240	4,52	1,16
30°	3,30	0,0612	0,0170	2,44	
34,3°	3,71	0,0290	0,0275	3,93	

Table XIII. Wing, with flap IIa. $\beta = 15^\circ$

α	c_r	$c_{w\infty}$	c_Q	$-c_p$	c_{m_h}
0°	0,77	0,0074	0,0085	1,08	
0°	0,77	0,0092	0,0053	0,98	
0°	0,75	0,0126	0,0034	0,89	
0°	0,68	0,0142	0,0020	0,73	
0°	0,50	0,0232	0	—	
5°	1,16	0,0077	0,0052	0,96	
5°	1,13	0,0101	0,0034	0,84	
5°	1,08	0,0128	0,0020	0,66	
10°	1,51	0,0061	0,0102	1,14	
10°	1,47	0,0101	0,0063	0,97	0,54
10°	1,43	0,0140	0,0035	0,77	
10°	1,29	0,0203	0,0021	0,49	
10°	1,18	0,0274	0	—	0,38
20°	2,24	0,0034	0,0214	1,59	
20°	2,22	0,0052	0,0157	1,35	
20°	2,10	0,0112	0,0099	0,99	
20°	1,96	0,0185	0,0065	0,65	0,61
20°	1,72	—	0	—	
30°	2,89	0,0036	0,0311	1,84	
30°	2,84	0,0107	0,0224	1,33	
30°	1,06	—	0	—	
32,5°	3,10	0,0059	0,0344	1,93	0,99
32,5°	1,07	—	0	—	0,37

Table XIV. Wing, with flap IIa. $\beta = 30^\circ$

α	c_r	$c_{w\infty}$	c_Q	$-c_p$	c_{m_h}
0°	1,41	0,0046	0,0103	2,25	
0°	1,36	0,0079	0,0065	1,95	0,66
0°	1,31	0,0121	0,0047	1,67	
0°	1,20	0,0182	0,0036	1,26	
0°	1,14	0,0295	0,0038	0,93	
0°	0,83	0,059	0	—	0,40
10°	2,20	0,0032	0,0239	3,06	
10°	2,17	0,0053	0,0153	2,57	
10°	2,08	0,0091	0,0096	2,10	
10°	1,94	0,0118	0,0061	1,56	0,76
10°	1,79	0,046	0,0055	0,82	
10°	1,49	0,051	0	—	
20°	2,80	0,0066	0,0207	2,75	
20°	2,71	0,0102	0,0146	2,19	
20°	2,57	0,0216	0,0100	1,37	
20°	2,13	—	0,0099	0,74	
20°	1,85	—	0	—	

Table XIV. Continued

α	c_r	$c_{w\infty}$	c_Q	$-c_p$	c_{m_h}
30°	3,40	0,0069	0,0314	3,16	
30°	3,27	0,0144	0,0238	2,27	
30°	1,14	—	0	—	
32,7°	3,64	0,0123	0,0331	2,79	1,13
32,7°	0,87	—	0	—	0,39

Table XV. Wing, with flap IIa. $\beta = 45^\circ$

α	c_r	$c_{w\infty}$	c_Q	$-c_p$	c_{m_h}
0°	2,04	0,0035	0,0185	3,96	1,00
0°	1,99	0,0036	0,0132	3,56	0,97
0°	1,84	0,0336	0,0093	2,14	0,87
0°	1,31	0,0788	0,0109	0,83	
0°	1,19	0,0801	0	—	0,57
10°	2,72	0,0035	0,0224	3,84	1,14
10°	2,69	0,0059	0,0157	3,28	
10°	2,59	0,0111	0,0112	2,57	
10°	1,90	0,0855	0,0144	1,00	
10°	1,75	0,0904	0	—	
20°	3,40	0,0041	0,0278	4,15	1,34
20°	3,31	0,0055	0,0217	3,56	1,29
20°	3,14	0,0123	0,0157	2,66	1,20
20°	2,51	0,0762	0,0216	1,48	
20°	1,86	0,1320	0	—	
29°	3,79	0,0099	0,0299	3,59	1,38
29,8°	1,43	—	0,0374	1,85	
29,8°	1,23	—	0	—	0,48

Table XVI. Wing, with flap IIa. $\beta = 60^\circ$

α	c_r	$c_{w\infty}$	c_Q	$-c_p$	c_{m_h}
0°	2,64	0,0030	0,0230	5,81	1,24
0°	2,66	0,0027	0,0224	5,75	

For low c_Q the flow fluctuates between adhering and seperated condition.

0°	1,84	0,1503	0	—	0,64
10°	3,32	0,0031	0,0262	5,32	
10°	3,26	0,0050	0,0195	4,34	1,40
10°	1,91	0,1612	0	—	
19,8°	3 82	0 0059	0,0283	5,11	1,56
20,2°	2,67	0,1700	0,0344	2,16	
23,5°	1,83	—	0,0343	1,8	
29,5°	1,26	—	0,0355	1,73	
30,0°	1,03	—	0,0355	1,58	
22,5°	1,46	—	0	—	0,51
30°	1,02	—	0	—	

Table XVII. Wing, with flap IIb.

α	c_r	$c_{w\infty}$	c_Q	$-c_p$
		$\beta = 30^\circ$.		
20°	2,73	0,0120	0,0139	2,97
20°	2,62	0,0166	0,0096	1,96
25°	3,12	0,0100	0,0213	4,22
25°	2,93	0,0183	0,0152	2,52
30°	3,42	0,0134	0,0257	4,66
30°	3,30	0,0192	0,0219	3,50
32,2°	3,54	0,0167	0,0268	4,42
		$\beta = 45^\circ$.		
20°	3,36	0,0081	0,0216	5,1
20°	3,15	0,0207	0,0152	3,32
25°	3,63	0,0125	0,0247	5,1
25°	3,57	0,0152	0,0228	4,55
29,2°	3,70	0,0156	0,0254	4,38
		$\beta = 60^\circ$.		
0°	2,64	0,0044	0,0135	5,7
6°	3,04	0,0066	0,0180	5,9
11,5°	3,27	0,0070	0,0214	6,4

Table XVIII. Wing, with flap IIc. $\beta = 15^0$

α	c_r	$c_{w\infty}$	c_Q	$-c_p$	c_{mh}
0⁰	0,82	0,0094	0,0086	1,24	
0⁰	0,79	0,0117	0,0055	1,01	
0⁰	0,72	0,0138	0,0032	0,83	
0⁰	0,66	0,0171	0,0017	0,64	
10⁰	1,53	0,0074	0,0104	1,41	
10⁰	1,45	0,0108	0,0062	1,03	
10⁰	1,38	0,0136	0,0039	0,80	0,47
10⁰	1,31	0,0164	0,0022	0,59	
32,8⁰	3,14	0,0082	0,0289	3,08	0,96

Table XIX. Wing, with flap IIc. $\beta = 30^0$

α	c_r	$c_{w\infty}$	c_Q	$-c_p$	c_{mh}
10⁰	1,98	0,0080	0,0112	3,29	
10⁰	1,86	0,0139	0,0072	2,46	
10⁰	1,74	0,0226	0,0043	1,77	0,66
10⁰	1,66	0,0320	0,0022	1,24	
15⁰	2,26	0,0098	0,0112	3,16	
15⁰	1,97	0,0293	0,0034	1,05	
20⁰	2,79	0,0076	0,0224	5,55	
20⁰	2,60	0,0126	0,0136	3,49	0,90
20⁰	2,52	0,0162	0,0098	2,47	
20⁰	2,45	0,0249	0,0078	1,77	
25⁰	3,06	0,0106	0,0221	5,13	
25⁰	2,86	0,0175	0,0152	3,26	
25⁰	2,68	—	0,0110	1,89	
30⁰	3,28	0,0180	0,0229	4,69	
30⁰	3,08	0,0266	0,0174	2,74	
32,5⁰	3,39	0,0203	0,0238	4,21	1,08

Table XX. Wing, with flap IIc. $\beta = 45^0$

α	c_r	$c_{w\infty}$	c_Q	$-c_p$	c_{mh}
10⁰	2,36	0,0230	0,0107	4,08	
10⁰	2,22	0,0350	0,0069	3,02	0,89
10⁰	2,14	0,0399	0,0043	2,33	
10⁰	1,78	—	0,0023	0,67	
20⁰	3,25	0,0196	0,0200	6,4	1,25
20⁰	2,89	0,0251	0,0123	3,79	
20⁰	2,74	0,0385	0,0092	2,70	
20⁰	2,67	0,0467	0,0066	1,91	0,95
25⁰	3,31	0,0260	0,0211	5,7	
25⁰	3,10	0,0341	0,0141	3,09	
30⁰	3,52	0,0297	0,0229	5,2	
30⁰	3,46	0,0374	0,0199	3,80	1,14
32,5⁰	3,66	0,0382	0,0246	4,50	1,17

Table XXI. Wing, with flap IIc. $\beta = 60^0$

α	c_r	$c_{w\infty}$	c_Q	$-c_p$	c_{mh}
10⁰	2,88	0,0210	0,0154	6,6	1,18
10⁰	2,69	0,0352	0,0108	4,73	
10⁰	2,64	0,0364	0,0072	3,71	
20⁰	3,39	0,0327	0,0178	5,9	
20⁰	3,24	0,0375	0,0127	3,86	1,22
25⁰	3,64	0,0341	0,0207	5,9	
25⁰	3,57	0,0385	0,0188	5,02	
27,6⁰	3,68	0,0406	0,0215	5,3	1,31

Table XXII. Wing, with flap IIa. Ground clearance a = 0.5t.

α	β	c_r	c_Q	$-c_p$
0⁰	30⁰	1,77	0,0075	1,49
0⁰	30⁰	1,64	0,0054	1,10
0⁰	30⁰	1,52	0,0050	0,63
0⁰	30⁰	1,23	0	—
5⁰	30⁰	2,02	0,0105	1,35
5⁰	30⁰	1,94	0,0074	0,90
5⁰	30⁰	1,81	0,0070	0,54
5⁰	30⁰	1,57	0	—
10⁰	30⁰	2,30	0,0163	1,38
10⁰	30⁰	2,27	0,01058	1,37
10⁰	30⁰	2,25	0,0118	0,86
10⁰	30⁰	1,79	0	—
15⁰	30⁰	2,54	0,0372	1,98
0⁰	45⁰	2,28	0,0156	2,19
0⁰	45⁰	2,17	0,0107	1,76
0⁰	45⁰	1,57	0	—
5⁰	45⁰	2,44	0,0196	2,11
5⁰	45⁰	2,36	0,0150	1,57
5⁰	45⁰	1,76	0	—
9,5⁰	45⁰	2,68	0,0318	2,36
9,5⁰	45⁰	1,96	0	—
0,8⁰	60⁰	2,55	0,0288	3,51
1,0⁰	60⁰	2,55	0,0288	3,46

Table XXIII. Wing, with flap IIa. Ground clearance a = 0.67t.

α	β	c_r	c_Q	$-c_p$	c_{mh}
10⁰	30⁰	2,20	0,0101	0,99	
10⁰	30⁰	1,79	0	—	
16,8⁰	30⁰	2,77	0,0324	2,15	
16,8⁰	30⁰	1,50	0	—	
12,8⁰	45⁰	2,86	0,0306	2,26	
12,8⁰	45⁰	1,70	0	—	
4,3⁰	60⁰	2,87	0,0300	3,69	
4,9⁰	60⁰	2,63	0,0305	2,44	
4,9⁰	60⁰	1,85	0	—	

Table XXIV. Wing, with flap IIa. Ground clearance a = 0.83t.

α	β	c_r	c_Q	$-c_p$	c_{mh}
15⁰	30⁰	2,54	0,0169	1,37	
15⁰	30⁰	1,95	0,0158	0,75	
15⁰	30⁰	1,79	0	—	
18,9⁰	30⁰	2,88	0,0336	2,26	
18,9⁰	30⁰	1,37	0	—	
10⁰	45⁰	2,65	0,0164	1,78	
10⁰	45⁰	2,07	0,0178	0,88	
14,3⁰	45⁰	2,93	0,0305	2,47	
0⁰	60⁰	2,66	0,0168	3,02	
0⁰	60⁰	1,75	0,0228	1,36	
0⁰	60⁰	1,64	0	—	
6,4⁰	60⁰	3,01	0,0300	3,86	
7,5⁰	60⁰	2,35	0,0330	2,55	
7,5⁰	60⁰	2,00	0	—	

Table XXV. Wing, with flap IIa. Ground clearance a = 1.5t.

α	β	c_r	c_Q	$-c_p$	c_{mh}
25,5⁰	30⁰	3,18	0,0312	2,41	1,06
21,8⁰	45⁰	3,30	0,0288	2,62	1,19
11,4⁰	60⁰	3,31	0,0265	4,26	1,33

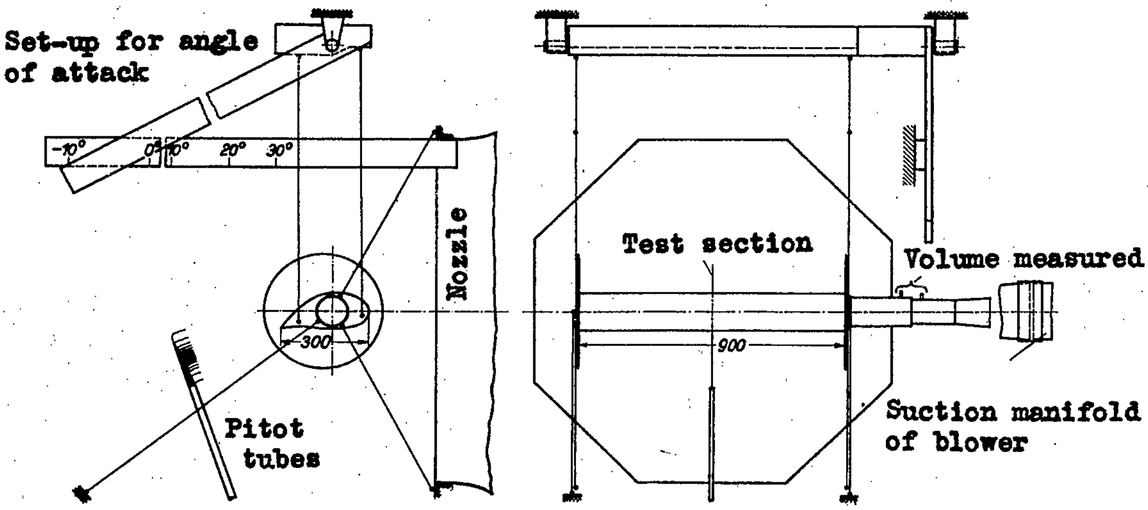


Figure 1.- Experimental set-up.

mm X .03937 = in.

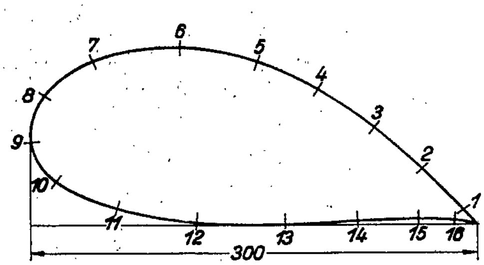


Figure 2.- Thick wing showing location of drilled holes for pressure measurements.

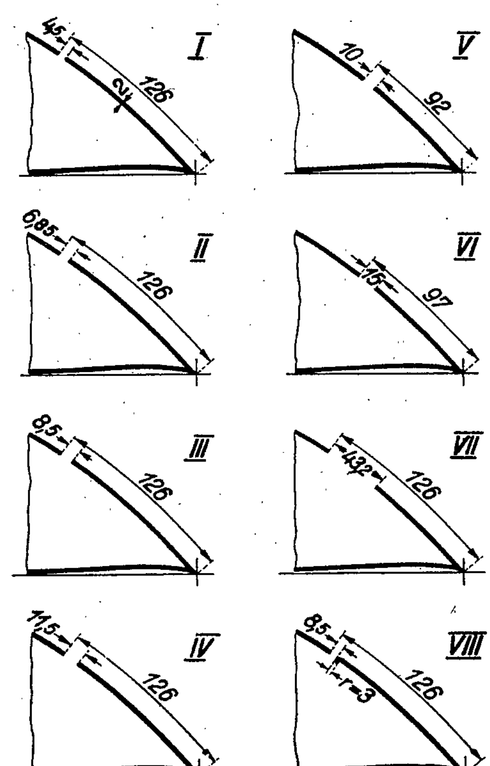
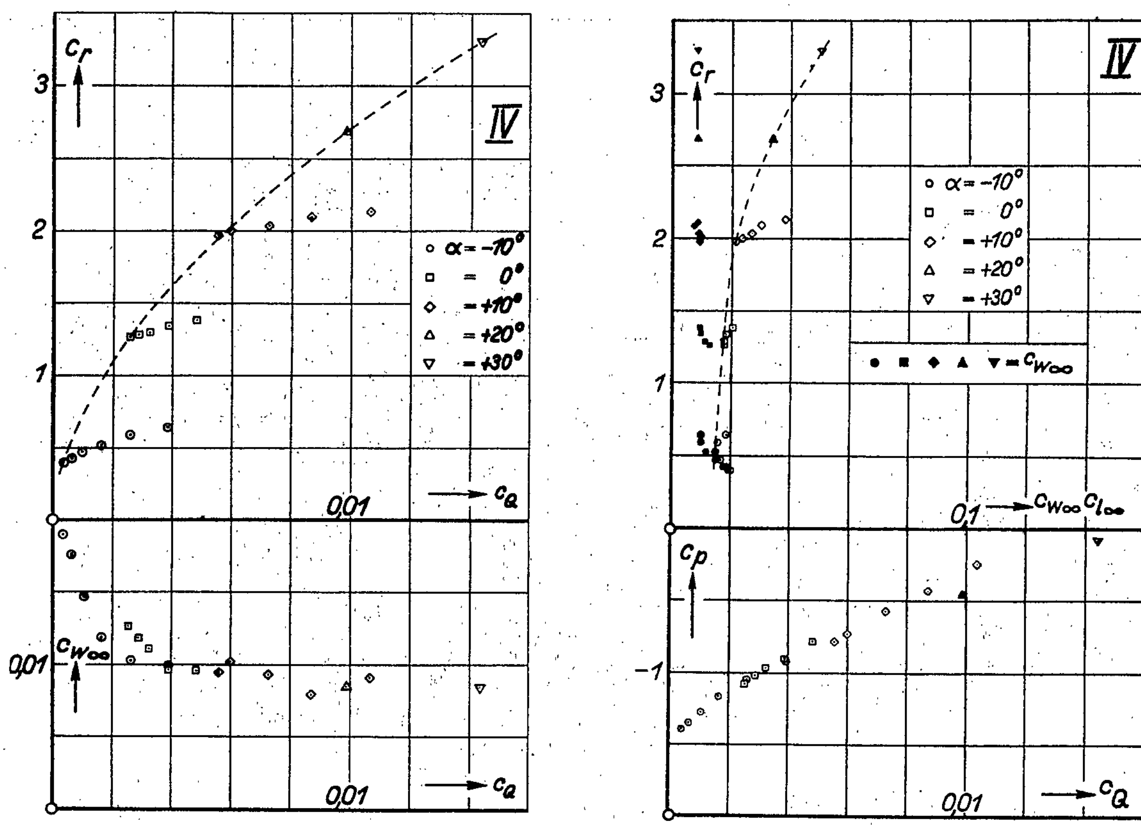


Figure 3.- Slot arrangements I to VIII for thick wing.



Figures 4,5.- Results with slot IV of thick wing.

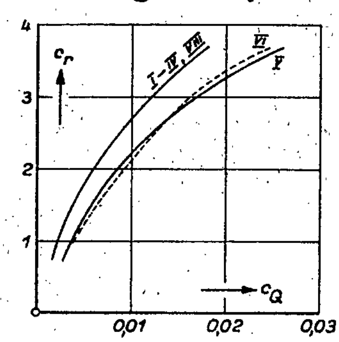


Figure 6.- Lift and suction volume for various slots.

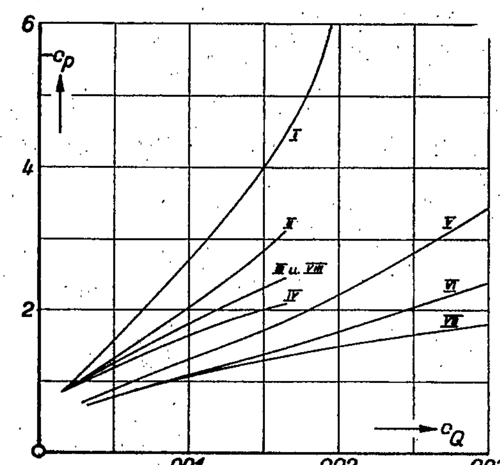


Figure 8.- Suction pressure and suction volume for various slots.

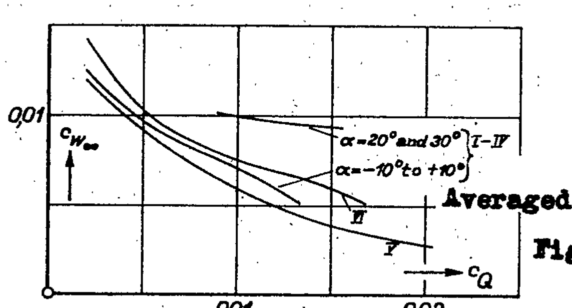


Figure 7.- Profile drag and suction volume for various slots.

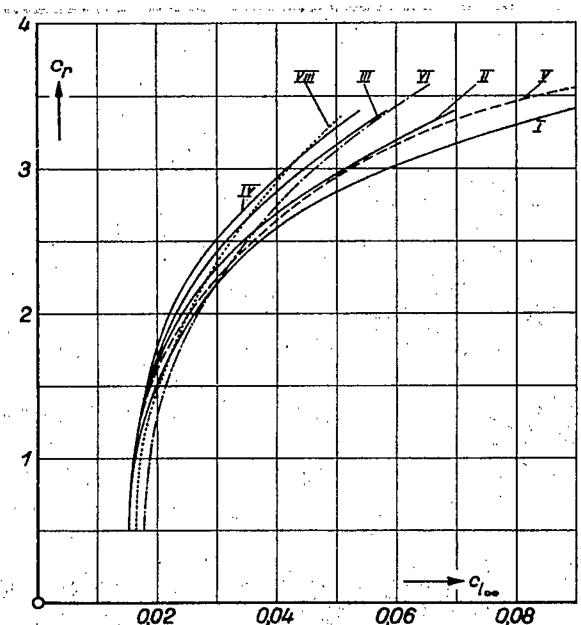


Figure 9.- Lift and profile efficiency for various slots.

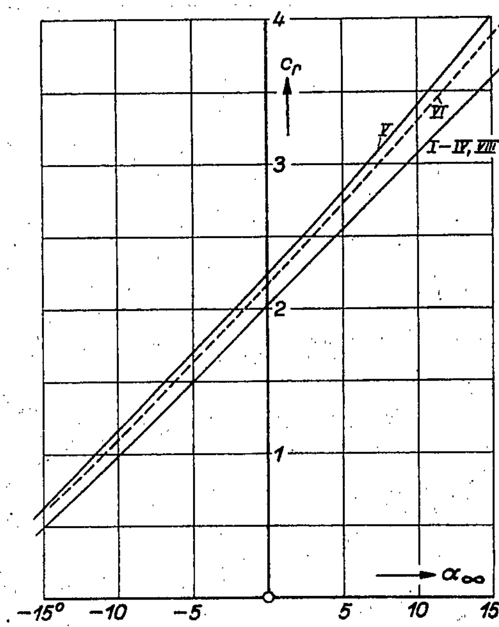


Figure 10.- Lift and angle of attack with wing of infinite span for various slots.

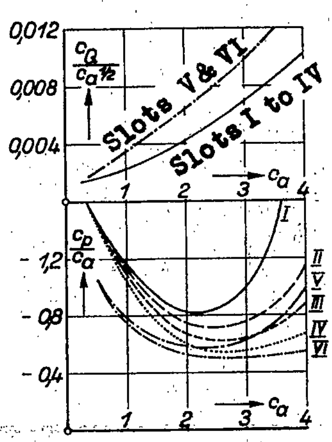


Figure 11.- Lift and suction factors for various slots.

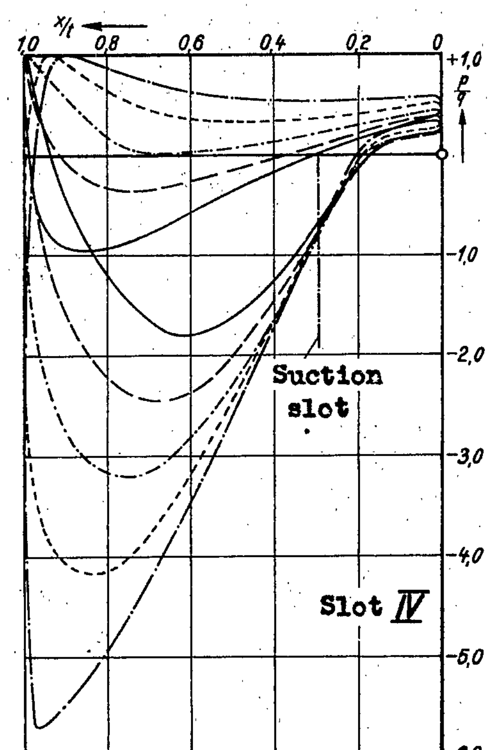


Figure 12.-Pressure distribution over thick airfoil with varying α, slot IV.

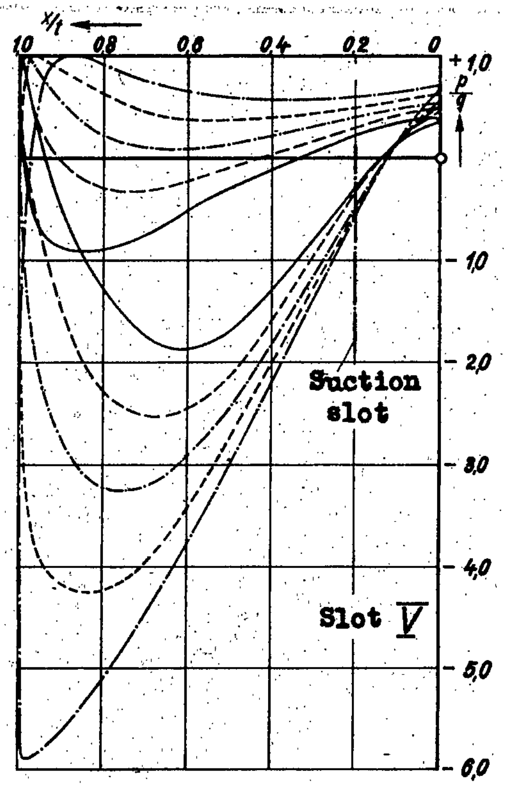


Figure 13.- Pressure distribution over thick airfoil with varying α, slot V.

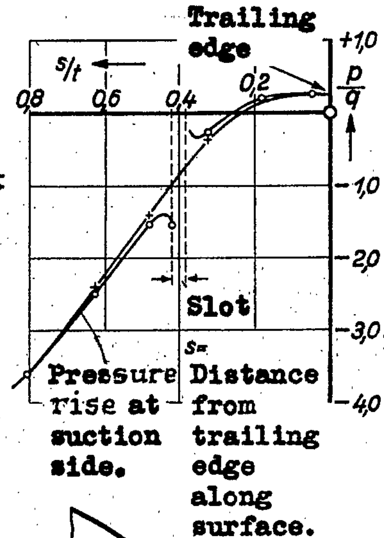


Figure 14.- Effect of sink on pressure distribution.

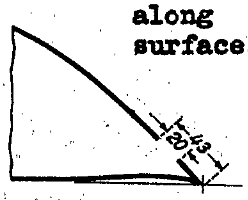


Figure 15.- Slot X near trailing edge of wing.

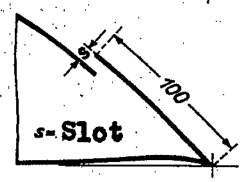


Figure 16.- Slot IX with over-lapping trailing edge.

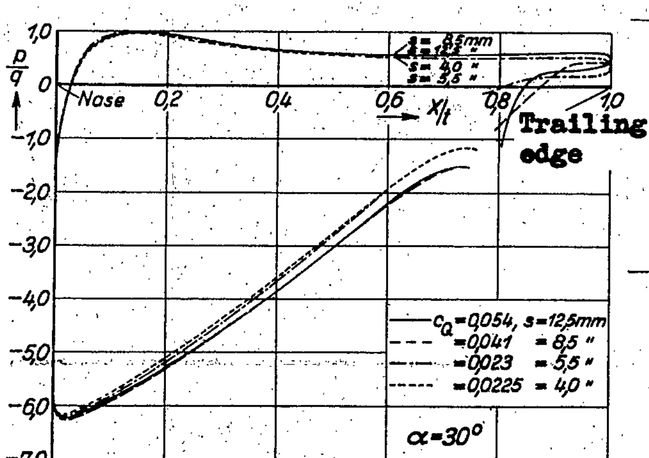


Figure 17.- Pressure distribution for slot IX.

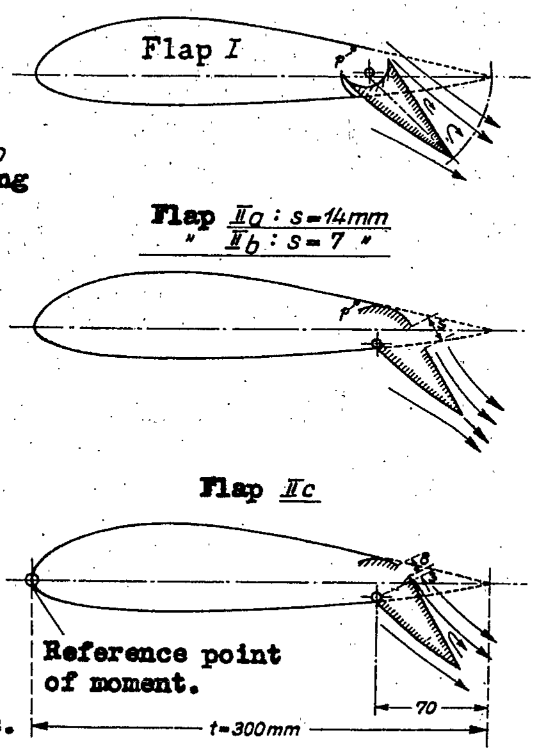


Figure 18.- Diagrams of wing flaps.

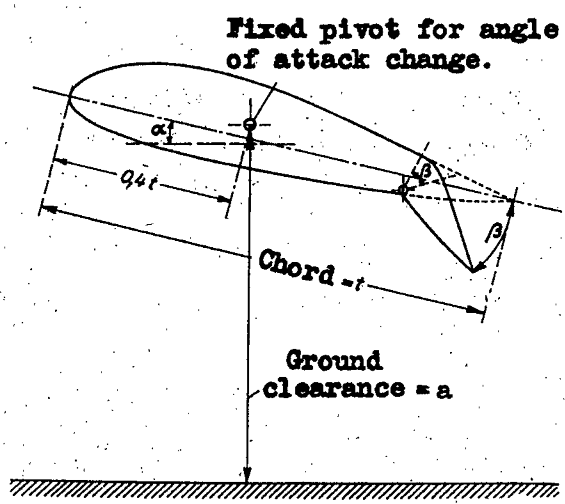


Figure 19.- Definition of angle, point of rotation and ground clearance of smooth wing.

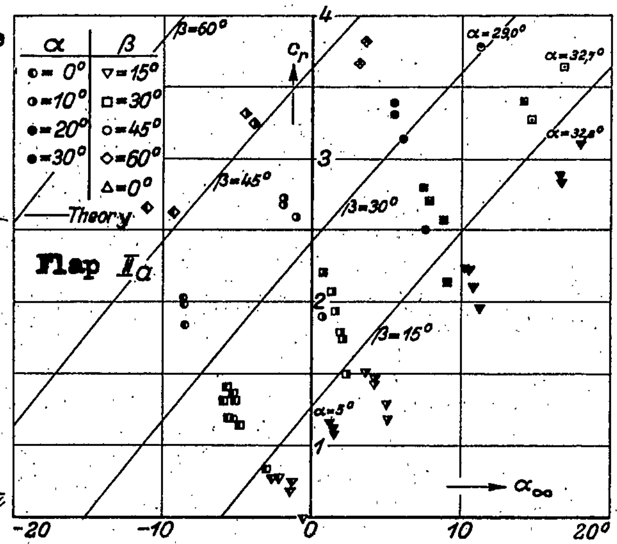


Figure 26.- Lift and speed factor of suction for flap II a.

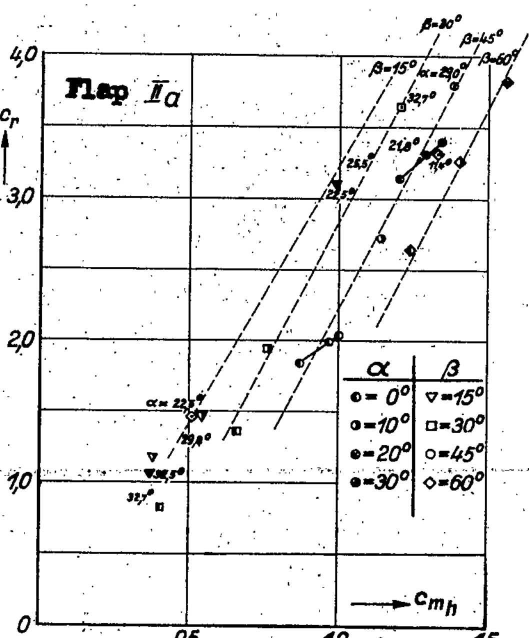


Figure 24.- Lift and yawing moment for flap II a.

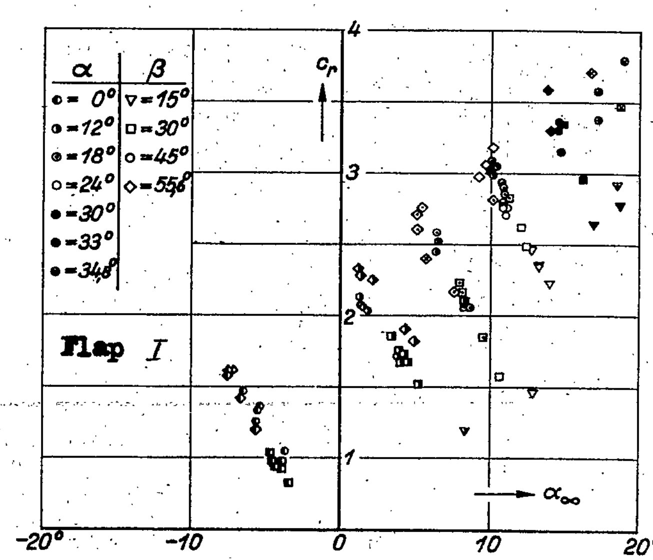


Figure 25.- Lift and angle, α for wing of infinite span, with flap I.

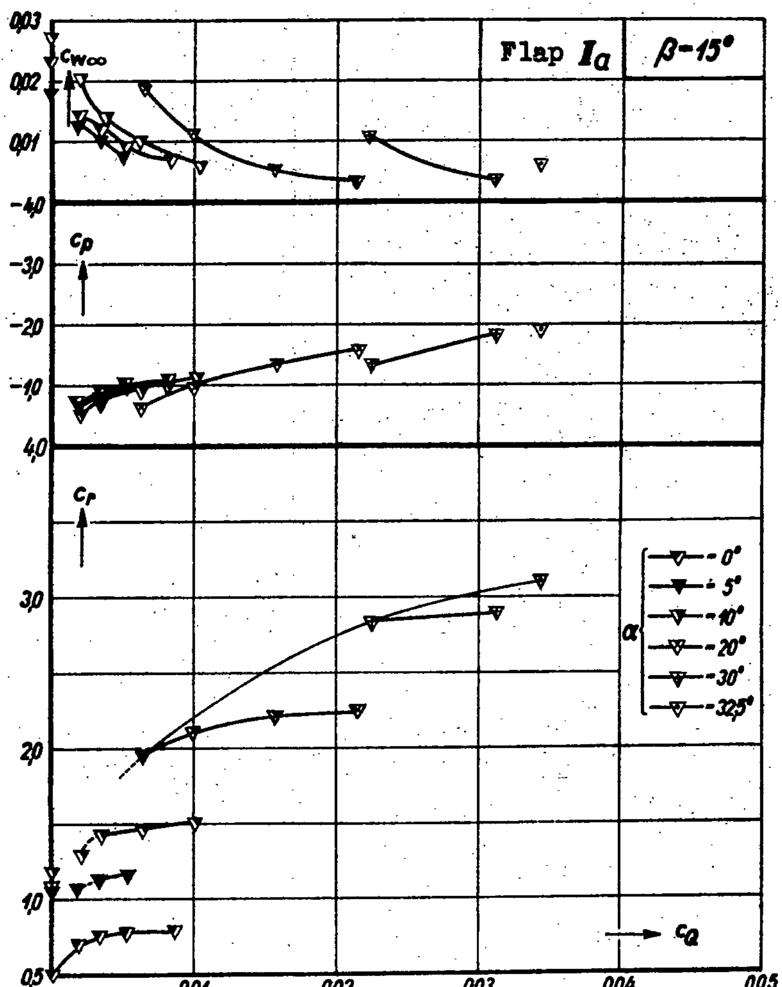


Figure 20.- Results for flap II a, lift, profile drag, suction pressure, suction volume (flap angle $\beta = 15^0$), for α see Figs. 4 & 5.

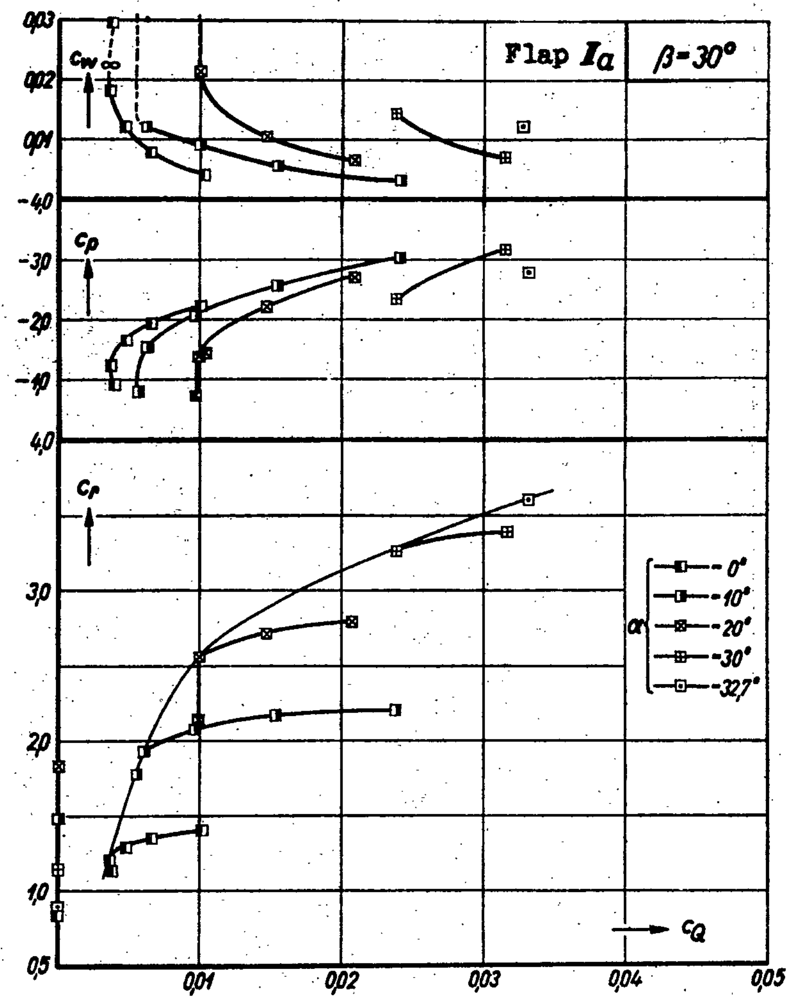


Figure 21.- Results for flap II a, $\beta = 30^0$.

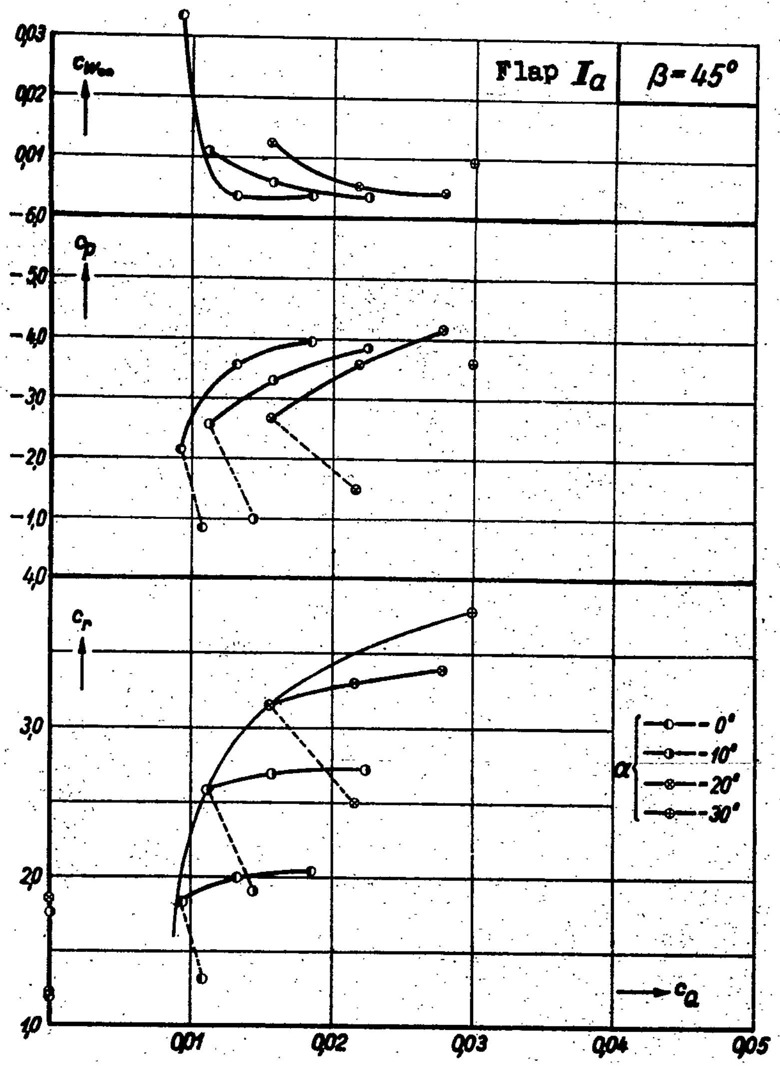


Figure 22.- Results for flap IIa, β = 45°.

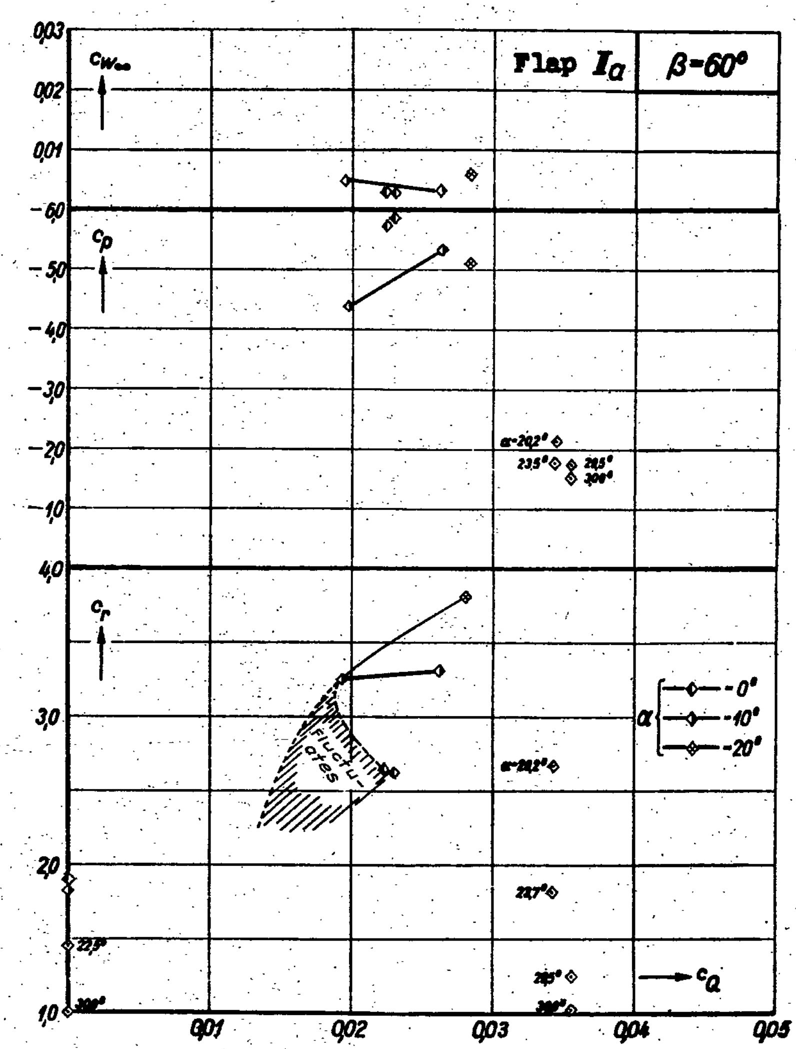


Figure 23.- Results for flap IIa, β = 60°.

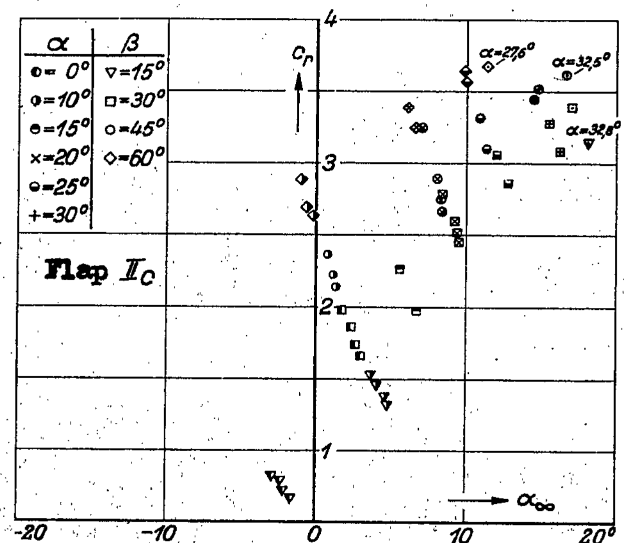


Figure 27.- Lift and angle, α for wing with infinite span, flap II c.

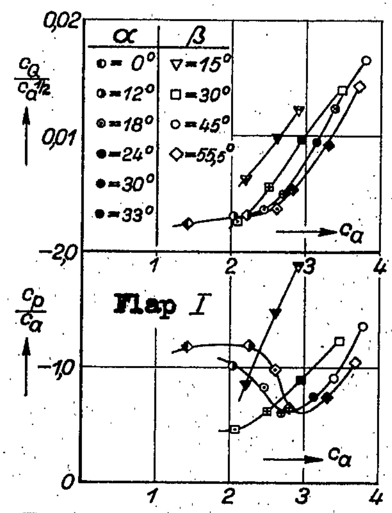


Figure 28.- Lift and speed factor of suction for flap I.

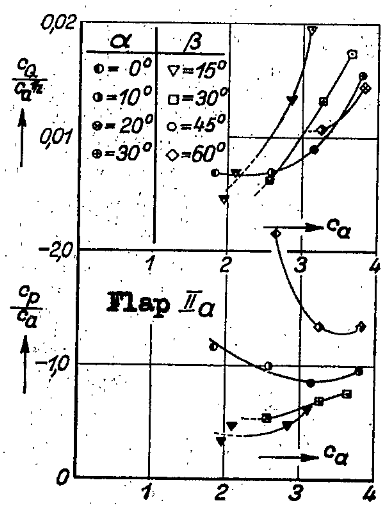


Figure 29.- Lift and angle, α for wing with infinite span, flap II c.

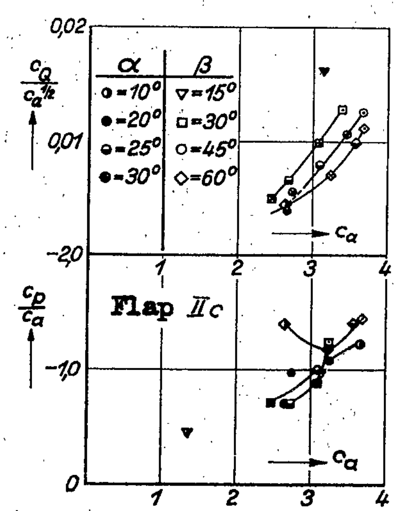


Figure 30.- Lift and speed factor of motion, flap II c.

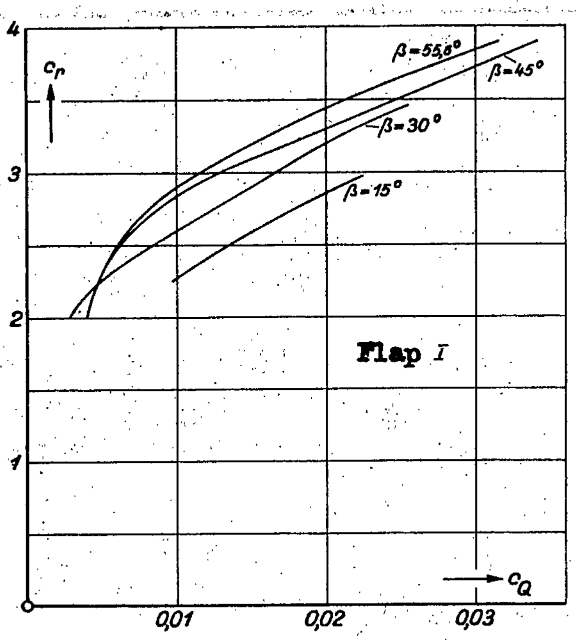


Figure 31.- Lift and suction volume, compiled for flap I.

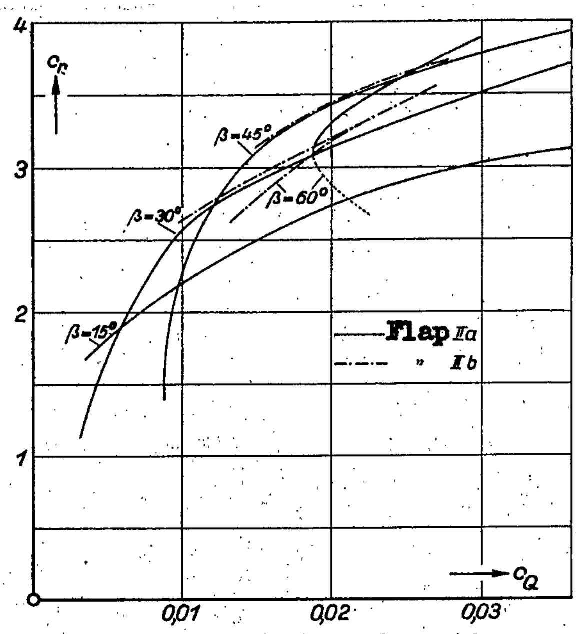


Figure 32.- Lift and suction volume, compiled for flaps II a and II b.

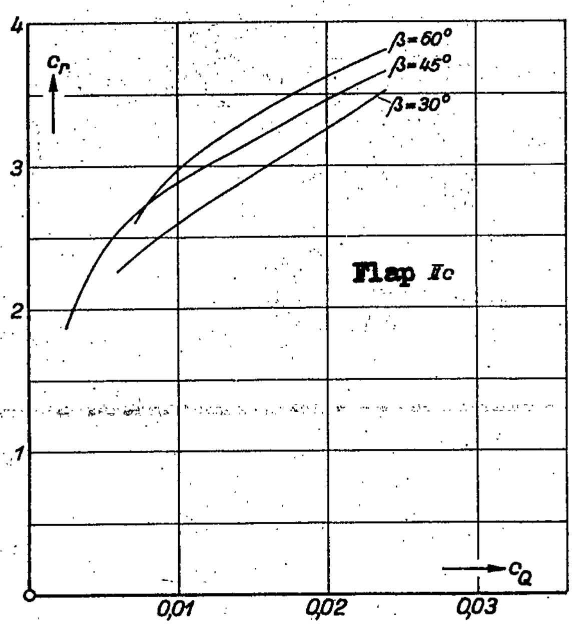


Figure 33.- Lift and suction volume, compiled for flap II c.

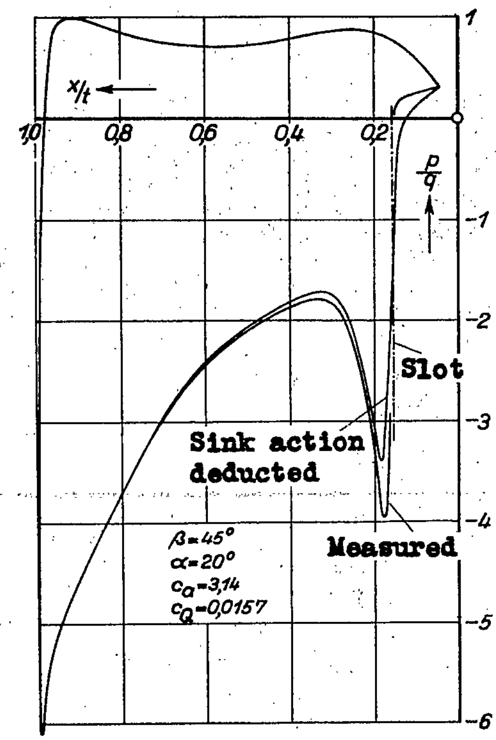


Figure 34.- Pressure distribution for flap II a.